Fifth Report To

The U.S. Congress

And

The U.S. Secretary Of Energy

From The

Nuclear Waste Technical Review Board

June 1992

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UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
1100 Wilson Boulevard, Suite 910
Arlington, VA 22209

June 3, 1992

The Honorable Thomas S. Foley
Speaker of the House
United States House of Representatives
Washington, D.C. 20515-6501

The Honorable Robert C. Byrd
President Pro Tempore
United States Senate
Washington, D.C. 20510-1902

The Honorable James D. Watkins
Secretary
U.S. Department of Energy
Washington, D.C. 20585

Dear Speaker Foley, Senator Byrd, and Secretary Watkins:

The Nuclear Waste Technical Review Board (the Board) herewith submits its *Fifth Report* as required by the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203.

Congress created the Board to evaluate the technical and scientific validity of the Department of Energy's (DOE) program to manage the permanent disposal of the nation's civilian spent fuel and high-level radioactive waste. Specifically, the Board is charged with evaluating the DOE's site-characterization activities at Yucca Mountain, Nevada, as well as activities relating to the design of the repository and to the packaging and transport of spent fuel and high-level radioactive waste.

Since its last report, in December 1991, the Board has continued its interaction with the DOE, the state of Nevada, and with others involved in or concerned about this important program. As a result of these interactions, the Board would like to make 15 recommendations that it believes will aid the DOE in its endeavors to design and implement a safe and efficient radioactive waste disposal system.

As in all of the Board's past reports, activities are reviewed and recommendations are presented based primarily on the breakdown of the Board's technical panels. This report is somewhat different, however, in that the Board has chosen to address an issue that it believes has wide-ranging implications for the entire waste management system: the thermal loading of a

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repository. The thermal-loading strategy used to control the temperatures in a repository will affect the design and long-term performance of the repository, as well as many other aspects of the waste management system, from spent fuel storage through final disposal. It is, therefore, a fundamental decision in the U.S. waste management program.

The Board has recommended that, before choosing a specific thermal-loading strategy, the DOE evaluate systematically the advantages and disadvantages of several different strategies. In this way, a strategy can be chosen that best assures the safe isolation of high-level radioactive waste. The Board's analysis of this issue is presented in detail in two chapters of the report, and four recommendations are devoted to the issue.

We thank you for the opportunity to serve the nation and Congress. As our work progresses, we hope to continue to assist you in furthering the goal of safe, efficient, and timely disposal of civilian high-level radioactive waste.

Sincerely,

Don U. Deere, Chairman

Clarence R. Allen

John E. Cantlon

Patrick Domenico

Donald Langmuir

D. Warner North

Dennis L. Price

Ellis D. Verink, Jr.

John J. McKetta

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Executive Summary

By 2030, after all existing commercial nuclear power plants in the United States have completed 40 years of operation, approximately 85,000 metric tons of radioactive waste from spent fuel will have accumulated for disposal. Congress assigned the U.S. Department of Energy (DOE) the responsibility to develop and implement a system to manage the disposal of this waste, along with approximately 9,000 metric tons of defense high-level radioactive waste from reprocessing.

In 1987, Congress directed the DOE to evaluate a site at Yucca Mountain, Nevada, for its suitability as a possible location for a mined geologic repository for the permanent disposal of that waste. In that same legislation, Congress created the Nuclear Waste Technical Review Board (the Board) to provide an independent source of expert advice on the technical and scientific aspects of the DOE's program.

Board Activities this Reporting Period

The issues and recommendations described in this report have evolved primarily as a result of activities undertaken by the Board and its panels from August 1, 1991, to January 31, 1992. During this period, the Board sponsored eight meetings. Important "cross-cutting" issues covered at these meetings include the DOE's program goals and schedules and the potential effects of thermal loading on the design of a repository. These issues, as well as the Board's specific recommendations for this reporting period, are discussed in detail in this report.

In addition to the Board's regular activities, Chairman Don U. Deere testified before Congress on March 9 and March 31, 1992. Although this did not take place within the August 1991 to January 1992 time frame, Dr. Deere's statements, along with a review of the DOE's testimony on its research priorities, have been included here. The full text of the Board's answers to follow-up questions posed by the Senate committee are provided in Appendix F.

Finally, the Board's makeup has changed recently. On February 18, 1992, President Bush appointed Dr. John J. McKetta to the Board. Dr. McKetta, a chemical engineer and professor emeritus from the University of Texas at Austin, will serve a four-year term. On April 19, 1992, after the completion of this report, Dr. Don U. Deere left the Board, ending his term as the first Chairman. As such, Dr. Deere was responsible for establishing the Board, organizing its panels, and overseeing its first years of operation. The terms of three other Board members also ended on April 19, and those vacancies are being filled by the White House.

DOE Program Goals and Schedules

The Board recognizes that priorities related to the civilian radioactive waste management program are reflected in and affected by schedule considerations and budget allocation decisions. It is important, therefore, that the Board understand how these decisions are made.

For this reason, on several occasions during the past year, John Bartlett, director of the DOE Office of Civilian Radioactive Waste Management (OCRWM), was invited to brief the Board on OCRWM research priorities and budget allocations. During these presentations and in his testimony before the congressional committees, Dr. Bartlett emphasized that the Secretary of Energy has two primary goals of equal rank for the program — to fulfill the DOE's contractual commitment to accept custody (at a monitored retrievable storage facility) of spent fuel from the utilities by 1998, and the initiation of permanent disposal at a repository by 2010. These two dates guide DOE decisions relating to program priorities and the allocation of funds among competing program elements.

The Board understands and supports the need for schedule targets to maintain program momentum. However, to meet the Secretary's goals, a number of major interim milestones will have to be met and uncertainties resolved. A delay in reaching any of these milestones, because of difficulties resolving any of the uncertainties, could challenge the OCRWM's ability to reach the Secretary's goals. Given the present status of site characterization and other technical and nontechnical factors that may be outside the DOE's control, there are significant uncertainties related to the current program schedule.

The Board believes that there may be some disadvantages associated with basing program priorities so heavily on the current schedule. For example, the current schedule (1) allows little time for the collection and analysis of underground data prior to license application; (2) allows little time to resolve unanticipated technical problems; (3) allows little time to resolve questions about unpredictable conditions important to the repository's performance; and (4) allows little time to evaluate the repository design and waste management system alternatives (such as long-lived waste packages or thermal-loading strategies).

Board Comments on Thermal-Loading Strategies

In its *First Report to the U.S. Congress and the U.S. Secretary of Energy*, the Board identified "thermal loading of a repository" as one issue that would have a large influence on a repository's long-term performance. The Board described thermal loading (thermal output of emplaced spent fuel per unit area of repository, usually expressed as kilowatts / acre) as a "cross-cutting issue." This is because the thermal-loading strategy chosen for a geologic repository will affect most other components of the system, including decisions about ageing, the repository size and design, the design of the waste package, as well as decisions about how the spent fuel will be stored and transported.

Initially, spent fuel has a high level of heat output. The heat decreases rapidly during the first few decades and then continues to decrease at a more modest rate for thousands of years. The heat given off by spent fuel and high-level radioactive waste is a major consideration in any strategy for waste isolation in a repository. Because the temperatures that will be experienced by the natural and engineered barriers can be predicted and controlled, it is possible to consider various thermal-loading strategies and choose that strategy that best assures the safe isolation of high-level radioactive waste.

In October 1991, the Board held a three-day meeting to learn more about the thermal loading of a repository. The major purpose was to review the rationale and effects of alternative thermal-loading strategies on design concepts for a high-level waste repository. A review was presented on the evolution and rationale leading to the current U.S. conceptual design (referred to as the reference, or baseline, concept) proposed for Yucca Mountain, Nevada. Simply stated, the current U.S. thermal-loading strategy calls for the disposal of relatively "young" spent fuel (e.g., as little as only 10 years out of the reactor). This means that high temperatures (above the boiling point of water) would be created in the immediate vicinity of the waste packages for approximately 300 to 1,000 years, followed by below-boiling temperatures. An important hypothesis behind the strategy is that a region surrounding the waste packages will dry out for the 300-to-1,000-year period and that liquid water, which could cause container corrosion and serve as a vehicle for the transport of radionuclides to the accessible environment, will not be present. This hypothesis has yet to be tested, however.

The specific details of the DOE's proposed thermal-loading strategy appear to have evolved incrementally over the last two decades, and a number of conditions have been assumed. Important documents relating to the evolution of the U.S. program clearly suggest that the DOE has always assumed high thermal loads for repositories in this country, regardless of the disposal environment. A comprehensive and systematic analysis of alternative, and potentially better, thermal-loading strategies (e.g., below-boiling temperatures, or above-boiling temperatures for 10,000 years or more) for the proposed Yucca Mountain site has not yet been completed. As a result, a firm scientific and technical basis for the DOE's current baseline thermal-loading strategy for the Yucca Mountain site does not exist.

The capacity of any repository for spent fuel and high-level waste is directly related to thermal loading. As a result, realistic estimates of the waste disposal capacity of the proposed Yucca Mountain site can be made only after underground exploration has been conducted and a thermal-loading strategy has been confirmed through a balanced combination of modeling and underground testing.

Finally, the discussions on thermal loading highlighted what Board members have emphasized on a number of occasions: Waste disposal must be looked at as a complex, *integrated* system. Thermal-loading decisions control the repository design, which in turn affects how and what decisions are made about other system components — such as the emplacement concept or the waste package design, fuel storage, and transportation.

Congressional Testimony on DOE Research Priorities

In testimony on March 9, 1992, before the House Appropriations Committee, Subcommittee on Energy and Water Development, Dr. Deere expressed the Board's continuing concern about two issues that it believes have special significance for the civilian radioactive waste management program: DOE's postponement of construction of the underground exploratory studies facility and its reduction of funding for research and development of an engineered barrier system.

The Board believes that further delays in the initiation of underground excavation and testing could lead to delays in determining whether or not Yucca Mountain is a suitable site. Furthermore, until the underground geology of the site can be better evaluated, it will be difficult to determine what total program costs will be. If sufficient and predictable long-term funding is not provided for necessary site-characterization activities, Congress and the Secretary of Energy should anticipate slippage in the current repository development schedule.

Citing budget constraints, the DOE has steadily reduced funding for research in the area of engineered barriers. The Board estimates that funding levels in the range of $10-15 million per year, over the next ten years, would probably be necessary to develop a credibly long-lived waste package. The Board has told the DOE that studies of the potential contribution of long-lived engineered barriers should be made a more important part of the program.

These concerns were reiterated by Dr. Deere in a hearing held on March 31, 1992, by the Senate Committee on Energy and Natural Resources. Dr. Deere identified two additional areas that will require research before the Secretary's goal of disposing of spent nuclear fuel by 2010 can be met. The first involves generating a research base for choosing the appropriate thermal-loading strategy for the proposed repository. As outlined above, many uncertainties about the current baseline thermal-loading strategy persist. The Board believes that testing the validity of alternative strategies should proceed as soon as possible in parallel with studies of the current baseline strategy.

A second issue raised at the March 31 Senate hearing concerned the importance of designing the various waste management functions (storage, transportation, and disposal) so that they work together safely and effectively as a *system*. The Board believes that the systemwide studies recently initiated by the DOE should be iterative, comprehensive, and timely so that near-term decisions affecting system design will not preclude alternatives that later may be shown to be preferable.

Board Recommendations

The recommendations made in the Board's reports are intended to aid the DOE in its efforts to improve the scientific work being conducted in the high-level radioactive waste management program. The following recommendations have resulted from activities undertaken by the Board and its panels during this reporting period. Recommendations pertaining to the cross-cutting issue of thermal loading are presented first in this summary. They are followed by recommendations arising from individual panel activities.

A. System Implications of Thermal Loading

1. The Board recommends that the DOE thoroughly investigate alternative thermal-loading strategies that are not overly constrained by a desire to rapidly dispose of spent fuel. This investigation should involve a systematic analysis of the *technical advantages and disadvantages* associated with the different thermal-loading strategies. An assessment of each strategy's implications for other elements of the waste management system also should be undertaken.

2. In assessing the different thermal-loading strategies, it is critical that special attention be paid to evaluating the uncertainties and, in particular, the critical hypotheses associated with each strategy. The Board strongly encourages the DOE to review its research plans to ensure that this evaluation be carried out through a balanced combination of modeling, field mapping, laboratory testing, long-term, large-scale underground testing, and, if appropriate, the study of natural analogues. This information could then allow the timely selection of a prudent thermal-loading strategy.

3. Since thermal loads lower than those proposed by the DOE's reference repository design could require the use of expansion areas adjacent to the proposed 1,520-acre repository site, any exploratory work in these expansion areas should be conducted with deliberation to avoid disqualifying the areas for potential use later on.

4. Care should be taken in making critical decisions, especially irreversible decisions, that could have negative implications for other components of the waste management system. This is particularly important in light of the fact that important systemwide trade-off studies have not been completed.

B. Geoengineering

1. The Board recommends that the DOE avoid making design decisions for the exploratory studies facility that could preclude repository configurations shown by the proposed system studies to provide superior performance. In particular, as previously recommended by the Board, opening sizes should be as small as functionally required. The potential for using conventional rail transport should not be eliminated through the construction of tunnels with excessive grades, unless repository operational studies show the proposed design to be appropriate.

2. The DOE should develop contingency plans for reduced funding levels that consider incremental approaches to excavating the Yucca Mountain block, possibly using one or two smaller tunnel boring machines, thus allowing early access across key underground geologic features.

3. The DOE should review and document the technology, practice, and experience developed by the Defense Nuclear Agency during the last 40 years for backfilling and sealing geologically contained nuclear explosions as part of its sealing program for a nuclear waste repository.

4. Exploration work in expansion areas adjoining the proposed site should be conducted with the same requirements as those placed on the presently designated repository area, since the boundaries are not yet fixed.

C. Tectonic Features and Processes

1. The Board recommends once again that the DOE give greater emphasis to seismic vulnerability studies. Discussions of site suitability, from the seismic point of view, should be based on the likelihood of adverse consequences and not on the occurrence of

earthquake ground motion or fault displacement alone.

2. The Board notes that important aspects of seismic risk assessment, particularly those associated with postclosure fault displacement within the repository block, cannot be carried out until exploratory underground excavation is well advanced and faults are exposed. The Board continues to recommend that underground excavation be given high priority.

3. As with other areas of concern, the Board recommends the DOE greatly increase emphasis on systems engineering studies. It notes that seismic issues should not be considered independently of other factors in the overall system — such as thermal loading, drift configuration, container emplacement, nature of the engineered barriers, and transportation systems.

D. The Engineered Barrier System

1. Waste package containment goals should exceed, not just meet, minimum regulatory requirements. To achieve this, the Board again strongly recommends that engineered barriers be viewed as an integral part of the radioactive waste management program, and that development and testing of robust, long-lived waste packages be funded dependably and at a level sufficient to evaluate their contribution to long-term predictions of repository behavior, and to total system safety.

2. The DOE should increase funding to the engineered barrier system program *before* repository-level geologic data become available for the Yucca Mountain site. Increased funding to the engineered barrier system program *after* site-specific geologic data start coming in may be viewed as an attempt to compensate for site deficiencies.

E. Transportation and Systems

1. The Board recommends that the DOE initiate and pursue vigorously top-level system trade-off studies so as to provide a firm, systemwide rationale for making the various major decisions that will affect the safety, efficiency, and design of the total waste management system.

2. The Board recommends that the DOE develop the necessary supporting documents for the implementation of system safety and human factors programs, including program plan and design requirements for human factors, as well as overall system safety.

Introduction

By 2030, after all existing U.S. commercial nuclear power plants have completed 40 years of operation, approximately 85,000 metric tons[1] of radioactive waste from spent nuclear fuel will require disposal. Congress assigned the U.S. Department of Energy (DOE) the responsibility to develop and implement a system to manage the disposal of this waste. Also included for disposal is the country's defense high-level radioactive waste from reprocessing. Some estimates project that up to 9,000 metric tons of defense high-level radioactive waste ultimately will need disposal.

Managing the nation's spent fuel and high-level radioactive waste is a major undertaking *and* a task of major importance — now and for the future. The successful completion of this program will require an unprecedented effort on the part of the DOE, as well as other federal and state agencies.

Creating a radioactive waste management system involves more than constructing a deep, geologic repository. It involves designing, developing, and implementing a complicated system to package, collect, transport, store (for either short or long periods of time), and finally dispose of spent fuel from public utilities and high-level waste from defense facilities.

Existing plans call for the design and construction of a deep geologic repository comprising surface and underground facilities that will allow for *safe, long-term* isolation of spent fuel and high-level waste. The repository and its components must be designed and constructed in such a way as to prevent the movement of dangerous radionuclides into the accessible environment for thousands of years. A transportation system must be developed to ensure the safe shipment of the spent fuel and high-level waste from locations nationwide to the repository site. All components must be designed in such a way that they *work together* safely and effectively as a system.

One major challenge involves demonstrating to the satisfaction of both the regulators and the scientific and lay public that workers in the system and the public at large can be adequately protected and that the highly radioactive material will remain safely isolated from the accessible environment for thousands of years. Because this is a first-of-a-kind project and because of the extended time periods involved, technical uncertainties regarding the long-term performance of a repository wherever it is located will persist even under the best of circumstances. The Nuclear Waste Technical Review Board (the Board) is firmly convinced, however, that it is possible to increase the technical community's — and the public's — confidence in geologic disposal by lowering levels of uncertainty.

In 1987, Congress chose a site at Yucca Mountain, Nevada, to be evaluated for its suitability as a possible location for a repository. In that same legislation Congress created the Board to provide an independent source of expert advice on the scientific and technical aspects of the DOE's program. The Board reviews the DOE's work, primarily through meet-

1 *The phrase "metric tons" is used throughout this report to mean "metric tons of heavy metal."*

ings with representatives of the DOE, its contractors, the national laboratories, the state of Nevada, the utilities, the regulators, and other agencies and organizations concerned with radioactive waste disposal. The Board submits reports on its findings, conclusions, and recommendations twice a year to Congress and the Secretary of Energy. Its *First Report* was released in March 1990.

One of the Board's immediate goals has been to promote better communication among the technical and scientific people involved in the waste management program. Board members also believe that interaction with experts involved in radioactive waste management programs in other countries is crucial. Although other programs are researching disposal in different geologic media, important research is underway from which the U.S. program has and can continue to gain valuable insight. The Board has initiated contact and remained in touch with experts in programs in Canada, Finland, Germany, Sweden, and Switzerland.

To help keep Board members apprised of the public arena in which nuclear waste management technology is being developed, the Board solicits the views of the public and environmental organizations on a variety of issues. Members and staff also attend relevant technical conferences, symposia, and workshops.

This fifth report, for the most part, summarizes the Board's activities from August 1, 1991, through January 31, 1992. Extensive background information on the dates and nature of the Board's meetings, meeting participants, the Board's panels and panel members, and DOE responses to previous recommendations have been included in the appendices of this report.

The Board's reports are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Chapter 1
Background

The Nuclear Waste Technical Review Board (the Board) addresses issues and makes recommendations in this report that have evolved primarily as a result of activities undertaken by the Board and its panels from August 1, 1991, to January 31, 1992. Some non-Board activities, which Board members took part in during this time, also are reviewed.

In addition to these activities, several more recent events are reviewed here. Board Chairman Don U. Deere testified before Congress twice, on March 9 and on March 31. Finally, the Board's makeup has changed recently, and that also is discussed below.

Board Activities this Reporting Period

From August 1991 through January 1992, the Board and its panels sponsored eight meetings. A chronological list of the Board's activities (beginning January 1991, and including those scheduled for the future) can be found in Appendix C. A list of the people who made presentations at Board- and panel-sponsored meetings has been included in Appendix D. These meetings are reviewed and the Board's recommendations are presented and discussed in Chapters 2, 3, and 4.

The Department of Energy (DOE) has made a good-faith effort to respond to the recommendations made in previous Board reports. Appendix E of this report contains the DOE's responses to recommendations made in the Board's *Fourth Report*. Inclusion of the DOE's responses does not necessarily imply Board concurrence.

Other Issues

A. Congressional Testimony

In testimony on March 9, 1992, before the House Appropriations Committee, Subcommittee on Energy and Water Development, Dr. Deere stated the Board's continuing concern about two issues that it believes have special significance for the civilian radioactive waste management program: the postponement of construction of the underground exploratory studies facility and reductions in funding for development of an engineered barrier system.

The Board believes that further delays in the initiation of underground excavation and testing could lead to delays in determining whether or not Yucca Mountain is a suitable site. Furthermore, until the underground geology of the site is better evaluated, it will be difficult to determine total program costs. If sufficient and predictable long-term funding is not provided for construction of the exploratory studies facility and for other necessary site-characterization activities, the Board believes that Congress and the Secretary should anticipate slippage in the current repository development schedule.

Citing budget constraints, the DOE has reduced funding for research in the area of engineered barriers development each year since 1989. The Board estimates that funding levels in the range of $10-15 million per year, over the next several years, would probably be necessary to develop an economically and technically acceptable long-lived waste package. The Board has told the DOE that studies of engineered barriers should be made a more important part of the program.

At the same hearing, Dr. John W. Bartlett, director of the DOE's Office of Civilian Radioactive Waste Management (OCRWM), stated that OCRWM's total budget request of almost $392 million for fiscal year 1993 is up 42 percent over the fiscal year 1992 appropriation. According to Dr. Bartlett, this amount will allow the DOE to make progress toward the Secretary's two primary goals for the program — receipt of spent fuel by 1998 and disposal by 2010.

The OCRWM's fiscal year 1993 request of $248 million for site evaluation at Yucca Mountain reflects a 50 percent increase over the $166 million appropriated for that purpose in fiscal year 1992. According to Dr. Bartlett, some of these additional funds would be used to procure drilling and tunneling equipment, so that underground excavation can commence by November 1993. (Dr. Deere clarified in his statement to the Subcommittee that the work the DOE has planned for November 1993 relates primarily to the construction of surface facilities and that actual underground excavation would probably not take place until the following year.)

In answer to questions from Subcommittee members, Dr. Bartlett stated that given adequate resources, the OCRWM will be able to complete site characterization in time to submit a license application for repository construction by 2001. The DOE estimates that total program costs will be approximately $6.3 billion; with $1 billion already having been spent and another $1 billion going to the state of Nevada and others for technical review. Approximately $700 million per year, over the next seven years, will be required to complete site evaluation, as it is currently conceived. However, Dr. Bartlett stated that actual costs will not be known until underground excavation and testing reveal the technical characteristics of the site.

At a hearing held on March 31, 1992, before the Senate Committee on Energy and Natural Resources, Dr. Deere reiterated the Board's views on the importance of early underground exploration and testing at the Yucca Mountain site and emphasized the Board's concern over funding cuts in research into engineered barriers. In addition to underground exploration and testing and the development of a long-lived waste package, Dr. Deere went on to identify other areas where work is required so that progress can be made toward the Secretary's goal of developing a repository by 2010.

One area the Board believes requires more research pertains to a fundamental parameter, the thermal-loading strategy. The DOE's choice of strategy will affect the design and long-term performance of a repository, as well as many other aspects of the waste management system from interim storage through final disposal and beyond. There are many uncertainties associated with the DOE's current baseline thermal-loading strategy, which evolved during the mid-1980s for the Yucca Mountain site. The Board believes that an evaluation of other strategies should proceed as soon as possible in parallel with studies of the baseline strategy.

Dr. Deere also pointed out in his statement that it is important that the various interdependent functions of waste management (storage, transportation, and disposal) be designed to work together safely and effectively as a *system*. The Board believes that the systemwide studies recently initiated by the DOE should be iterative, comprehensive, and timely so that decisions affecting system design will not preclude alternatives that later may be shown to be preferable.

Following the Senate hearing the Board was asked to respond in writing to 12 follow-up questions. The answers were submitted to the Senate Committee on April 22, 1992. Highlights of these questions and the Board's answers can be found in Box 1.1., and the full text of both the questions and answers is provided in Appendix F.

B. DOE Presentations to the Board on Program Goals and Schedules

The Board increasingly has come to recognize that priorities related to the civilian radioactive waste management program are reflected in and affected by schedule considerations and budget allocation decisions. Consequently, to be able to adequately evaluate the technical and scientific aspects of the program, it is important that the Board understand how these decisions are made.

Box 1.1 — Board Response to Follow-Up Questions from the Senate Committee on Energy and Natural Resources*

— *Won't we know until 2001 even if the site [at Yucca Mountain] is unsuitable?*

Given the DOE's current schedule for completing the ESF, the determination of site suitability may not come much before 2001.... The DOE ... assumes that the probability of finding any disqualifying conditions at the Yucca Mountain site is very low. The Board is somewhat less confident of such a finding and believes that substantial underground excavation and testing will be required to make this determination. The Board is concerned that delays in the initiation of underground excavation and testing could lead to delays in the identification of potentially disqualifying conditions.

— *In your opinion, has the Department [of Energy] developed the appropriate priorities for getting the job [site characterization] done?*

The Board believes that both underground work and surface-based testing should proceed in parallel. The DOE should refocus its efforts ... so that both the thermal-loading strategy and the potential contribution of long-lived engineered barriers can be included in overall system-performance studies.

— *A significant amount of money is spent ... on so-called prelicensing activities and interaction with NRC. Is this interaction necessary at this juncture?*

The Board believes that participating in prelicensing activities and interacting with the NRC are the most efficient and cost-effective ways for the DOE to seek clarification of the NRC licensing requirements. Because a facility of this kind has not previously been licensed anywhere in the world, details related to regulatory requirements and their implementation may have to evolve over time.

— *Have we designed regulatory requirements for storage and disposal of nuclear waste that are so stringent that we are destined to fail?*

At this point, the Board is not aware of any technical problems such that the proposed repository or other elements of the storage, transport, and disposal system are "destined to fail,"... [h]owever, the regulatory framework is complex, and ... [t]he Board believes that ambiguities and potential inconsistencies in the regulatory framework need technical clarification. [I]t would be difficult to make safety standards less stringent unless a large majority of the public believes that such a change does not compromise their health and safety or that of future generations.

— *How will it be possible to prove the performance of Yucca Mountain for 10,000 years? Is it possible to prove anything for that long?*

The assessment of long-term repository performance will be based on the analysis of scientific data and informed judgment. The Board is optimistic that adequate and reasonable technical and scientific judgements about the geologic barriers to radionuclide migration can be made to support conclusions on repository performance for 10,000 years within the current regulatory framework. Because 100 percent assurance is not possible on even short-term predictions of natural geologic processes, the Board has repeatedly emphasized that added confidence in long-term waste isolation can be gained by incorporating robust engineered barriers.

— *If it costs $6 billion to study the suitability of the Yucca Mountain site and only $2 billion to build a repository at the site, then why not go ahead and build a test facility and see if it works?*

It has been suggested that waste could be more quickly and more cheaply emplaced in an *unlicensed* "demonstration facility." Although this approach at first appears attractive, it has numerous and significant disadvantages. First, without the extensive site-characterization data ... chances increase that the integrity of the disposal site could be compromised by poor design decisions. Second, the same lack of data would preclude long-term predictions on the behavior of the "demonstration facility." [T]he only way to verify the performance of the facility would be to monitor its performance for thousands of years. If, at some point, the facility's performance were found to be unacceptable, the facility would have to be modified, or all of the waste would have to be removed and a new site found. Finally, it is not at all clear that the public would accept the development of an unlicensed "demonstration facility."

**The full text of both the questions and the Board's responses is provided in Appendix F.*

For this reason, during the past year, Dr. Bartlett and several OCRWM associate directors were invited to brief the Board on OCRWM's research priorities and budget allocations. During these presentations Dr. Bartlett emphasized that the Secretary of Energy has two primary goals for the program: the receipt of spent fuel from the utilities by 1998 at a monitored retrievable storage facility, and the initiation of permanent disposal by 2010. According to Dr. Bartlett, these two goals of equal rank guide DOE decisions relating to program priorities and the allocation of funds among competing program elements. An important interim milestone in the attainment of the 2010 goal is the DOE's submission of an application by 2001 to the Nuclear Regulatory Commission (NRC) for a license to construct a repository.

Dr. Bartlett pointed out in his presentation that to meet the Secretary's goal for starting disposal by 2010, a number of other major interim milestones will have to be met:

- initiate construction of the exploratory studies facility by November 1993;
- evaluate site suitability as soon as possible;
- if site is found suitable, submit license application in 2001;
- commence repository construction in 2004.

A number of factors could delay progress in meeting the 2010 goal. As presented by Dr. Bartlett, these include:

- discovery that the Yucca Mountain candidate site is not suitable;
- political or legal obstacles;
- difficulty in resolving site-suitability and licensing issues;
- continuing evolution of regulatory requirements;
- insufficient program funding.

Following Dr. Bartlett's presentation, Mr. Carl Gertz, OCRWM associate director for Geologic Disposal, briefed the Board on the allocation of funds for the site-characterization program. Mr. Gertz stated that in fiscal year 1992, costs for compliance and regulatory support, support facilities and equipment, management and administration, interaction with various oversight groups, and financial and technical assistance, were about $120 million, or approximately two-thirds of the total funds allocated for site evaluation. These costs, which appear to be budgeted to support site-characterization activities at future projected peak levels of $700 million per year, were reported likely to remain relatively constant until site evaluation is completed. Maintaining base program expenditures at levels appropriate to support a full-scale, seven-year site-characterization program, has left about $60 million for site-characterization and design activities in fiscal year 1992.

C. Observations

It appears that a negative outcome or delay in the resolution of any of the aforementioned issues, many of which are outside the DOE's control, could challenge the OCRWM's ability to reach the Secretary's goals on schedule.

The Board understands and supports the need for schedules with target deadlines to maintain program momentum. However, there may be some disadvantages associated with basing program priorities so heavily on the current schedule. For example, (1) the DOE's current plans allow a relatively short time period for the collection and analysis of underground data prior to license application; (2) the short time frame does not allow for resolving *unanticipated* technical problems involved with constructing the exploratory studies facility, nor with obtaining adequate, consistent data for site characterization; (3) it leaves little time to resolve questions about unpredictable conditions important to the repository's performance; and (4) there is little opportunity to evaluate repository design and waste management system alternatives (such as long-lived waste packages or alternative thermal-loading strategies for the repository).

Budget considerations also play an important role in setting OCRWM program priorities. The DOE cited a $30 million cut in its appropriation for fiscal year 1992 in explaining its decisions to delay construction of the exploratory studies facility and to reduce funding for the development of an engineered barrier system.

D. Conclusions

1. The Secretary's goals for the program — the receipt of spent fuel by 1998 (at a monitored retrievable storage facility) and the initiation of disposal by 2010 — together with budget considerations are primary factors underlying DOE program priorities.

2. Given the Secretary's schedule and the OCRWM's priority on surface-based testing, near-term increases in funding levels over those received in fiscal year 1992 will be required to begin and continue underground exploration and testing.

3. It will be difficult to estimate long-term funding requirements accurately until the underground geology at the Yucca Mountain site is better evaluated. However, it seems certain to the Board that each year of delay in getting underground for exploration and characterization of the repository horizon will add more to the overall costs of the project because of the DOE's base program costs.

4. Given the present status of site characterization and other technical and nontechnical factors that may be outside the DOE's control, there are significant uncertainties related to the current long-term schedule.

E. Changes in Board Makeup

On February 18, 1992, President George Bush appointed Dr. John J. McKetta to the Board. Dr. McKetta, a chemical engineer and professor emeritus from the University of Texas at Austin, will serve a four-year term. Board members are appointed from a slate of nominees submitted to the President by the National Academy of Sciences.

On April 19, 1992, after completion of this report, Dr. Don U. Deere left the Board, completing his term as member and Chairman. President Ronald Reagan appointed Dr. Deere to the Board and named him its first Chairman on January 18, 1989. As such, Dr. Deere was responsible for establishing the Board, organizing its panels, and overseeing its first years of operation.

Dr. Deere brought to the Board more than 45 years of experience working as an international consultant on hydroelectric projects, tunnels, and landslides. He has served for the past 25 years as a consultant on the Washington, D.C., metro system, and more recently has worked with the consortium of British and French contractors who have designed and are constructing the channel tunnels connecting Great Britain to the continent.

In addition to Dr. Deere, three other members completed their terms on the Board in April. These vacancies are now being filled by the White House.

Chapter 2
Panel Activities, Findings, and Conclusions

This chapter describes activities, findings, and conclusions based on various panel activities. (See Appendix A for a breakdown of the Board's panels.) Where the Board's investigation and research have progressed sufficiently since the previous report, recommendations are included. Some of the issues raised here have not yet been examined thoroughly enough by the Board to warrant recommendations at this time.

Recommendations made in this chapter are intended to inform Congress and to aid the DOE in its efforts to improve the technical work being conducted as part of site characterization at Yucca Mountain and to identify areas for possible investigation.

Geoengineering

On September 18 and 19, 1991, Board members were briefed in Las Vegas, Nevada, on the Yucca Mountain Site Characterization Project Office's revised preliminary design for the exploratory studies facility, the design approach, and the recommended schedule for construction. Because of its timeliness, information from this meeting was included in the Board's *Fourth Report to the U.S. Congress and the U.S. Secretary of Energy,* published in December 1991.

For this reporting period, the Board's activities relating to geoengineering focused primarily on coordinating a meeting on thermal loading, which has a technical scope and breadth that cuts across all of the Board's panel activities. In planning the meeting, the Board sought the participation of organizations in addition to the DOE and its contractors and supporting national laboratories. At the resulting three-day meeting, held from October 8 to 10, 1991, in Las Vegas, Nevada, the Board reviewed the effects of alternative thermal-loading strategies on high-level waste repository design concepts. Because of its cross-cutting nature, the issue of thermal loading is reviewed in depth in Chapters 3 and 4 of this report. This section will review those aspects of thermal loading that should be considered during the ongoing design of the exploratory studies facility and during any possible revisions to the repository conceptual design.

On November 12 and 13, 1991, Board members were briefed in Seattle, Washington, on the technical requirements as well as on current and planned activities of the DOE's repository sealing program. The issues raised at this meeting are discussed in Section B below.

A. The Exploratory Studies Facility and Repository System Design Enhancements

During the past three years, the Board has followed closely the evolution and preliminary design of the exploratory studies facility because of its importance to the site-characterization program and because the exploratory studies facility will become part of the repository if Yucca Mountain is found suitable and is licensed for repository development. Important topics discussed at the thermal-loading meeting were the enhancements and other factors that potentially could affect the design of a geologic repository.

The Board places particular importance on discussions of repository system design enhancements, such as alternative waste package concepts and emplacement modes, backfill, and enhancements for controlling thermal effects on the repository. The concept of in-situ ageing of spent fuel by means of drift emplacement and ventilation and by the use of heat pipes to improve the effective thermal conductivity of the host rock are repository enhancements that should receive close evaluation by the DOE. The evolution of other programs (e.g., the Swedish geologic repository concept) away from the emplacement of small waste packages in boreholes and toward the emplacement of large waste packages in drifts is very consistent with the Board's continuing emphasis on the need to investigate and develop robust, long-lived, multipurpose waste package concepts. (The engineered barrier system is discussed later in this chapter.)

It is important that decisions not be made during exploratory studies facility design that may preclude the future incorporation of some of these concepts and enhancements. For example, large casks appropriate for drift emplacement could weigh in excess of 100 tons. Movement of such heavy structures can best be implemented by steel wheels on steel rails; traction requirements limit rail grades normally to no more than 1.5 to 2.0 percent. Nonstandard traction techniques such as cogways, cableways, or even the use of tracked vehicles would permit higher grades, but at a reduced throughput, which could adversely affect the planned emplacement of 3,000 tons of spent fuel and 400 tons of high-level waste per year. The current design for the north access of the exploratory studies facility has grades in the range of 6 to 7 percent. The south access is designed to have a grade of less than 2 percent, and the DOE has suggested that if rail transport of waste into the repository should become desirable, it would be a simple matter to use the south ramp, rather than the north ramp, as planned. However, there does not appear to be any analysis on the operation of a repository using large heavy casks for waste emplacement. This raises several questions. For example, will using the south entrance as a waste ramp adversely affect surface or underground activities, and might there be a need for *two* accesses for the movement of large casks into the repository? These questions should be examined before irreversible decisions are made.

Similarly, the current repository design criteria require repository accesses and drifts to remain structurally stable for at least 84 years before the repository is backfilled and sealed; and the quantities of cement, grout, and organics used for construction of the underground openings also should be minimized (DOE, SCP - 1988). These design criteria, coupled with the potential for significant temperature-induced stresses in the rock resulting from the above-boiling thermal-loading strategy proposed by the DOE, would call for the underground openings to be as small as functionally practical. Small openings are more stable than large openings, all other things being equal. Drift emplacement of large casks — should this become desirable — could be implemented in 16- to 18-foot diameter tunnels.

Under the current plan, 25-foot diameter tunnels are required to allow the waste canisters to be rotated vertically so that they can be placed in vertical boreholes, which would be excavated in the floors of the tunnels. It is not clear, however, that borehole emplacement is the ideal emplacement mode. The Board questions the current requirement for the large, 25-foot diameter tunnels. Although an 18-foot diameter circular tunnel could readily be expanded to a 25-foot high horseshoe-shaped tunnel — should that prove necessary — a 25-foot circular tunnel, once excavated, could not be reduced in size.

Design decisions about the exploratory studies facility should be made carefully so as not to preclude potential repository configurations that might prove preferable as a result of further analysis. Such potentially important considerations should be factored into ongoing design efforts on the exploratory studies facility to avoid irreversible decisions that could adversely affect the final repository's ability to meet performance requirements. The Board believes that more emphasis should be placed on ensuring the long-term performance of the repository, rather than on meeting schedule deadlines. (See discussions of schedule priorities in Chapter 3.)

The Board's *Fourth Report to the U.S. Congress and the U.S. Secretary of Energy,* published in December 1991, concluded that underground access across key geologic features to visually examine and evaluate those features is critical to determining site suitability and recommended that access be made an early goal regardless of budget constraints. It was explained that this could be achieved through the development of contingency plans that consider an incremental approach to the excavations into the Yucca Mountain block, possibly using one or two smaller tunnel boring machines. The program, as currently planned, calls for the procurement of four new machines and projects access to key underground geologic features for 1996 at the earliest. The need for four machines has not been supported through consideration of alternative construction scenarios using two machines. It is possible that more efficiency could be achieved with fewer machines and with proper planning, improvements in the schedule might even result.

B. Repository Sealing Program

The Board was impressed by the scope and depth of the DOE's research, development, and design work conducted during the past decade on the repository sealing program. All aspects of the program appear to have been well planned and implemented, and although some of the work was conducted eight to ten years ago, the results are readily applicable to current program needs.

No reference has been made, however, to information or experience obtained from the backfill and sealing techniques developed by the Defense Nuclear Agency as part of the nuclear weapons testing program during the past 40 years. Several hundred nuclear detonations have been contained within the geologic formations at Rainier Mesa and Frenchman's Flat near Yucca Mountain. This containment has resulted from the development and implementation of effective backfill and sealing techniques. Such existing technology should be thoroughly assessed by the DOE for potential application to its program.

The Board was particularly pleased to learn that event trees and performance scenarios are being developed for the sealing systems and that repository sealing systems will be part of a repository performance assessment to be carried out by Sandia National Laboratories. The Board is looking forward to reviewing the results of this assessment, and particularly the confirmation of the preliminary conclusion that due to the high fracture permeability of the welded tuff in which the repository is to be sited, the potential for the repository drifts providing preferential flow paths is very small and thus the performance of the drift sealing systems will have little effect on overall repository performance.

One issue remains a concern to the Board. The total area needed for the proposed repository has not yet been verified, and this cannot be done until underground exploration has been conducted, a thermal-loading strategy affirmed, and a repository designed. (See discussion of thermal-loading strategies in Chapters 3 and 4). Therefore, any exploratory work in areas adjoining the proposed site, particularly those areas identified by the DOE as potential expansion areas, should be conducted with the same care and deliberation as within the proposed site.

C. Conclusions

1. A systemwide study of alternative thermal-loading strategies should be undertaken. Alternative waste package concepts and emplacement modes, backfill, and enhancements for controlling thermal effects in the repository could be considered as part of the repository conceptual design for this study.

2. The exploratory studies facility should not be designed such that any alternative repository design is precluded. As the design evolves, care should be taken not to make decisions that ultimately could constrain the selection of repository configurations.

3. The program as currently planned continues to call for the procurement of four tunnel boring machines and projects access to key underground geologic features for 1996 at the earliest. As discussed in the Board's *Fourth Report to the U.S. Congress and the U.S. Secretary of Energy*, the DOE should develop contingency plans. These plans should consider incremental approaches to excavations into the Yucca Mountain block, possibly using one or two smaller tunnel boring machines. In addition to being less costly, improvements in the schedule could even result.

4. Because the total area required for the proposed repository has not yet been verified, exploratory

work in potential expansion areas adjoining the proposed repository should be conducted with the same care and deliberation as within the proposed site.

5. Backfill and sealing technology, such as that developed by the Defense Nuclear Agency over the past 40 years, exists and could be useful to the DOE in this program.

D. Recommendations

1. The Board recommends that the DOE avoid making design decisions for the exploratory studies facility that could preclude potential repository configurations shown by the proposed system studies to provide superior performance. In particular, as previously recommended by the Board, opening sizes should be as small as functionally required. The potential for using conventional rail transport should not be eliminated through the construction of tunnels with excessive grades, unless repository operational studies show the proposed design to be appropriate.

2. The DOE should develop contingency plans for reduced funding levels that consider incremental approaches to excavating the Yucca Mountain block, possibly using one or two smaller tunnel boring machines, thus allowing early access across key underground geologic features.

3. The DOE should review and document the technology, practice, and experience developed by the Defense Nuclear Agency during the last 40 years for backfilling and sealing geologically contained nuclear explosions as part of the DOE's sealing program for a nuclear waste repository.

4. Exploration work in expansion areas adjoining the proposed site should be conducted with the same requirements as those placed on the presently designated repository area, since the boundaries are not yet fixed.

Tectonic Features and Processes

In the past, the Board has discussed several topics related to tectonic features and processes. In its fourth report, for example, the Board addressed the issue of *volcanism*, urging the use of a structured probabilistic approach to identify the important input assumptions that control the estimated volcanic hazard, and urging increased emphasis on evaluation of volcanic vulnerabilities of the proposed repository. During the past six months, the Board has devoted most of its efforts to *seismic issues* and, in particular, seismic vulnerabilities. These efforts follow the Board's recommendations in its second report that "increased emphasis be placed on understanding the engineering, public safety, and environmental consequences of seismic events at Yucca Mountain..." and that "discussions of site suitability should be based on the likelihood of adverse consequences and not on the occurrence of earthquake ground motion and fault displacement alone."

On January 22 and 23, 1992, the Panel on Structural Geology & Geoengineering held a meeting in Irvine, California, on the topic of seismic vulnerabilities. Presentations were made by the DOE and its contractors, the Nuclear Regulatory Commission (NRC), the Center for Nuclear Waste Regulatory Analysis, the state of Nevada, the Electric Power Research Institute (EPRI), the American Society of Civil Engineers, and the U.S. Geological Survey. Valuable insights were obtained regarding the behavior of tunnels during nuclear testing at the Nevada Test Site, worldwide geologic investigations, the design and performance of engineered surface and subsurface facilities exposed to earthquakes, and the licensing of nuclear power plants.

Following is an update of the Board's views on seismic vulnerabilities of the proposed repository and the use of this information in the decision-making process. Included is a discussion of the effects of systems considerations on seismic risk.

Potentially, the proposed repository and its appurtenant facilities could be affected primarily by two earthquake-related phenomena: vibratory ground motion and fault displacement. These are discussed separately below. The effects of earthquakes on the hydrologic regime are not discussed in this report.

A. Seismic Vulnerabilities: Vibratory Ground Motion

This section examines the effects of vibratory ground motion (seismic shaking), which potentially would radiate outward from a rupturing fault or faults. The vibratory ground motion produced by earthquakes can cause serious damage, and under certain circumstances, particularly those related to local soil conditions, the damage could occur even at great distances from the causative fault.

When analyzing potential seismic vulnerabilities of the proposed repository, two phases of repository operation must be considered: a 100-year preclosure period and the 10,000-year (or longer) postclosure period. During the preclosure phase, the weakest link would appear to be the proposed surface waste-handling facility. Of most concern would be the hot cells, where the spent fuel shipped to the repository from the nuclear power plants or interim storage facilities is removed from transportation casks and transferred to disposal containers. (System changes that could obviate the need for hot cells are discussed below.) Design of buildings, such as the waste-handling building, to withstand strong vibratory ground motion is a well-understood and accepted procedure in the engineering community. Designs for nuclear power plants, which are much more complex and potentially more dangerous facilities than the proposed waste-handling building (primarily because reactor accidents can cause release of large amounts of radionuclides immediately), routinely take vibratory ground motion into account.

For example, nuclear power plants, such as those at the San Onofre and Diablo Canyon sites in seismically active coastal California, are built to safely withstand intense, long-duration earthquake ground motions whose peak accelerations are 0.7 g (gravity) and higher. These motions are assumed to result from earthquakes of magnitude 7.0 to 7.5 that may occur on nearby faults. This is also the upper magnitude range of hypothetical earthquakes near Yucca Mountain that the DOE is examining for ground-motion considerations. The Board has no specific suggestions at this time as to what that appropriate design level is. However, based on past experience, the Board does believe that designing preclosure surface facilities to safely withstand earthquake-related ground motion at Yucca Mountain is within the realm of well-accepted, sound engineering practice.

Underground seismic vulnerabilities also must be considered during the preclosure phase, but they are similar to those faced during postclosure, with several exceptions. In the preclosure phase, consideration must be given to operational safety during earthquakes because of the waste emplacement process. Operational safety during earthquakes, however, is not unique to the repository but is well understood because of experience in the operation of underground facilities of all kinds. On the other hand, the possible loss of waste containment due to the breaching of containers is primarily a concern during the long postclosure phase when retrievability (and possible accident mitigation) may no longer be an option. According to the current concept, the containers will be buried in boreholes off tunnels approximately 300 meters beneath the surface of Yucca Mountain.

In general, subsurface facilities worldwide have fared well during earthquakes. It has often been observed that ground motions from earthquakes decrease with depth. For example, during the 1980 earthquake, which caused great damage to certain parts of Mexico City, the nearby underground subway system came through with relatively little damage. At other locations close to earthquake fracture zones, this decrease may not be as pronounced, particularly when the underground structure itself is very close to the rupturing fault, as conceivably could be the case at Yucca Mountain.

Perhaps the most relevant analogue for determining the effects of vibratory ground motion on underground structures from nearby earthquakes may be the observations made at the Nevada Test Site. For more than 30 years, underground nuclear devices of different yields have been detonated, and the effects on nearby tunnels and underground structures have been observed. Ground-motion accelerations greatly in excess of those experienced during earthquakes have been recorded. Although there are real differences between earthquake ground motions and those caused by a nuclear explosion, there is ample evidence that normal, sound engineering practice that takes into account the quality of the rock and provides for an appropriate tunnel support system will be able to protect the proposed underground repository from the direct vibratory effects of very large earthquakes.

The DOE has correctly pointed out that because the postclosure phase extends for thousands of years, more than one earthquake could occur, and the effects of multiple earthquakes should be taken into account, particularly in the case of emplacement boreholes. The extrapolation of damage data from one earthquake or one nuclear test to the effects of repeated earthquakes requires caution. In this light, the Board believes that an understanding of the failure modes of the repository and components, such as containers, during this extended time is an important element in determining what the most damaging characteristics of earthquake ground motion would be, how the site could affect these characteristics, and how the resulting ground motion could be accommodated during design. Unfortunately, the DOE has made only limited progress in this area. In general, however, the Board views earthquake-related vibratory ground motion as primarily an issue of appropriate design and construction, rather than an issue of site suitability.

B. Seismic Vulnerabilities: Fault Displacement

In the preclosure period, again, the area of greatest concern would be the hot cell within the proposed waste-handling building. Although structures have been designed to accommodate fault displacement, such design is not common practice among engineers. There appears to be general agreement that designing a building to accommodate several centimeters or even several tens of centimeters of fault offset (depending partly on whether the fault offset is vertical or horizontal) can be accomplished and can be accepted by the engineering community at large. Designing for offsets of one meter or more would be much more demanding, although this has, in fact, been done for a very few structures in the past.

As a result of the lack of engineering experience, the DOE's strategy is to avoid locating critical parts of the surface facility directly above active faults. Any residual uncertainty about undiscovered small faults or the very small likelihood of new faulting (see the discussion below) could be accommodated in the building design. It has been pointed out that modularization of the building, that is, breaking it up into smaller elements, can increase the resistance to fault offset. The success of this fault-avoidance strategy would be dependent upon the ability of the DOE and its geologic contractors to detect the presence of faults. Initial trenching in Midway Valley, the proposed site of the waste-handling building, indicates a stratigraphy (that is, sediment layering) that would be clear enough to detect several centimeters of vertical offset during the past tens or even hundreds of thousands of years. This is encouraging with respect to the ability to demonstrate the presence or absence of active faults beneath the waste-handling building.

With respect to the underground repository, again, the most relevant data set appears to be that collected from the behavior of tunnels at the Nevada Test Site, where nearby nuclear explosions have sometimes caused movement along preexisting faults. When a fault appeared perpendicular to the tunnel, subsidiary fracturing was localized to rock close to the actual fault itself. When a fault intersected the tunnel at a shallow angle, the damage occurred over a wider zone because the fault displacement was close to the tunnel over that zone. Again it was shown that, if necessary, critical structures could be designed to withstand 50 centimeters or more of fault displacement in the tunnel wall. With respect to the repository, the current baseline concept calls for a 7.5-centimeter air gap between the borehole wall (rock) and the container. Increasing the spacing between the rock and container could decrease the vulnerability of these containers to small fault displacements. (See discussion below on system considerations.)

The DOE strategy with respect to underground faulting (and one shared by other nations planning geologic repositories) is to avoid significant faults in emplacing the waste containers. The success of such a strategy depends on the ability to detect such faults, the number of faults encountered, their potential for displacement, and, as previously indicated, their location and orientation. Based on surface data alone, there appears to be one fault (the Ghost Dance Fault) that transects the repository and several sets of faults (the Solitario Canyon Fault and the Imbricate Fault Zone), which are close to, or possibly overlap, its boundary. Experience in the tuff formations in the adjacent Nevada Test Site indicates that there are often more faults at depth than can be observed at the surface. From surface-based observations, the faults that could intersect the repository have low or indeterminate rates of movement. The feasibility of the fault-avoidance strategy, as well as the suitability of the site itself, may very well depend on the locations and characteristics of faults at the repository depth. Again, the Board strongly urges the DOE to proceed as rapidly as possible with exploratory drifts to assess the nature of faulting at the repository depth in Yucca Mountain.

Another important issue with respect to the strategy of fault avoidance is the likelihood of new faulting, that is, the rupture of previously unfractured rock. If we assume that future faulting would be restricted to preexisting faults, the problem is reduced to one of avoiding those preexisting faults. If new primary, or even secondary, faulting can credibly occur during the lifetime of the repository, the strategy of fault avoidance becomes much more difficult. Based on worldwide experience, the documented appearance during earthquakes of new faults—primary or secondary—is exceedingly rare. Those few cases that have been observed appear to be limited mainly to the minor extensions of faults beyond the extent of previous rupture, and to the fraying-out of faults or the appearance of minor tensile cracks in near-surface, unconsolidated deposits.

There are, however, several locations of possible new faulting that have not yet been thoroughly investigated, including one short rupture that may have first broken during the 1932 Cedar Mountain earthquake in west-central Nevada. This earthquake was associated with ruptures of at least 25 individual surficial faults, over a very wide area (65 x 13 kilometers). All but one reportedly occurred on preexisting fractures. Because new faulting cannot be ruled out categorically, its likelihood must be regarded as small but finite. (All faults, of course, had to be initiated at some time, but it appears that most originated as minor fractures, which then coalesced and extended their lengths in succeeding earthquakes.)

The question is, given the tectonic history of a region, how large is the likelihood of a new rupture? Initial studies by EPRI indicate that, depending on a number of debatable assumptions, undefined secondary faulting may be a greater contributor to container failure than the primary rupture itself. Nevertheless, it appears to the Board that if it can be shown by underground geologic mapping at Yucca Mountain that a given length of tunnel has not been broken by faulting (primary *or* secondary) during the hundreds of earthquakes that must have occurred nearby over the past 13 million years (the age of the Yucca Mountain tuffs), then a new break in this same tunnel segment during the next 10,000 years is exceedingly unlikely.

C. Systems Considerations and Seismic Risk

Seismic risk is an area of concern for the proposed Yucca Mountain repository for which, once again, a systems engineering approach is necessary. From its earliest days, the Board has urged the DOE to use more of a systems approach in its planning than it has in the past, whereby final engineering decisions will be made in light of optimizing the entire operation, rather than by considering individual elements, such as seismic risk, independently of other concerns. Two examples can be pointed out in which such a systems approach might significantly affect the engineering response to seismic risk.

1. The current reference, or baseline, design calls for transferring spent fuel from transportation casks to disposal containers at the surface loading facility, necessitating the use of hot cells and necessarily leading to some possibility, however small, of accidents during major earthquakes in the preclosure period. However, also under consideration is a universal cask, which would be used for both functions, thereby eliminating the need for hot cells and reducing the seismic exposure at the loading facility to a level that may not be significantly different from that at any other point in the transportation system. In deciding whether or not to use a universal cask, seismic risk should certainly be considered.

2. The vulnerability of the stored spent fuel to underground fault displacements, particularly during the postclosure period, may be a function of the method

of container emplacement within the bedrock of Yucca Mountain. It may not be realistically possible to demonstrate that no fault displacement—however minor—will ever occur through a container site. Therefore, the accommodation of a given small amount of displacement using appropriate engineering design may be more practical than attempting to locate minor faults. As described previously, the current reference design calls for emplacement in vertical boreholes, only slightly larger than the containers themselves, drilled into the floors of the branch drifts. Ongoing studies of optimal thermal loading and engineered barriers leave open the possibility of storing the containers in different configurations, such as with larger air gaps, or on the floor of the emplacement drifts themselves, with or without backfill. Such layouts might have significant positive impact on the containers' ability to accommodate local fault displacements. However, there would have to be general engineering consensus that such displacement-protective systems would indeed be realistic and adequately conservative. Such concepts, if adopted, could very well affect the extent of fault studies necessary during site characterization.

In summary, the Board emphasizes once again that seismic issues cannot be considered independently of other factors in the overall system, such as thermal loading, drift configuration, the nature of the engineered barriers, and transportation systems. There is no doubt that seismic risk could be reduced considerably by a number of engineering and planning measures, but whether these are necessarily called for, or whether the trade-offs are practical and economic, can best be determined by considering seismic risk in the context of the total waste management system.

D. Other Issues

In its *Second Report,* the Board discussed the importance of developing geologic criteria and standards that reflect the nature and relative vulnerability of the repository. In this light, the Board has been following the discussions associated with the draft seismic guidelines promulgated by the NRC staff and is impressed with the manner in which the NRC staff have solicited critical comments from different quarters and have modified these guidelines as it has seen appropriate.

The Board also has made several recommendations to the DOE about the need to incorporate input from outside experts into its studies. In its *Fourth Report,* the Board pointed to the successful use of outside experts in the performance assessment being carried out for the Waste Isolation Pilot Project in New Mexico. With respect to seismic issues at Yucca Mountain, the Board notes that EPRI also is using input from outside experts, including earth scientists presently or formerly affiliated with the state of Nevada. The Board believes that the DOE can learn from these efforts.

E. Conclusions

1. In general, the Board views earthquake-related vibratory ground motion as primarily an issue of appropriate design and construction, rather than an issue of site suitability. This conclusion applies to both the surface and underground facilities, and to both the preclosure and postclosure operational phases.

2. The Board is optimistic that faults with potentially significant displacements during future large earthquakes can be identified during site characterization, both beneath critical surface facilities and within the underground repository. These faults should generally be avoided. Faults with potential displacements of only a few centimeters or more can probably be accommodated by appropriate design.

3. The likelihood of the appearance of significant new faults at Yucca Mountain during earthquakes over the next 10,000 years is low. Furthermore, if underground exposures show that rock units have not been broken since their deposition some 13 million years ago, then a new break forming in these same rocks within the next 10,000 years is exceedingly unlikely.

4. Timely resolution of important seismic issues depends critically upon commencement and progress of underground characterization activities.

5. There is no doubt that seismic risk to Yucca Mountain facilities could be considerably reduced by a number of engineering and planning measures. Whether these are necessarily called for, however, or whether the trade-offs are practical or economic, can best be determined by considering seismic risk in the context of the total waste management system.

F. Recommendations

1. The Board recommends once again that the DOE give greater emphasis to seismic vulnerability studies. Discussions of site suitability, from the seismic point of view, should be based on the likelihood of adverse consequences and not on the occurrence of earthquake ground motion or fault displacement alone.

2. The Board notes that important aspects of seismic risk assessment, particularly those associated with postclosure fault displacement within the repository block, cannot be carried out until exploratory underground excavation is well advanced and faults are exposed. The Board continues to recommend that underground excavation be given high priority.

3. As with other areas of concern, the Board recommends the DOE greatly increase its emphasis on systems engineering studies. It notes that seismic issues should not be considered independently of other factors in the overall system — such as thermal loading, drift configuration, container emplacement, nature of the engineered barriers, and transportation systems.

The Engineered Barrier System

In keeping with the intent of the regulations, the Board has begun to include in its definition of the "engineered barrier system" all barriers designed or engineered by humans. The engineered barrier *system* refers to all *components* of the waste disposal system that have been designed, engineered, or constructed to prevent the release of radionuclides into the accessible environment. Components of the engineered barrier system include the waste form (spent fuel rod assemblies or borosilicate glass containing high-level waste from reprocessing); the waste package, which includes the waste form and any other containers; any material placed over and around the waste package; and materials that could be used to backfill the openings in the repository. These — working together with the natural, geologic setting — are expected to prevent, or greatly retard, the migration of radionuclides to the accessible environment. Given this definition, the repository design and the choice of thermal-loading strategy play critical roles in the design of an engineered barrier system. (See Chapter 3 for a discussion of various thermal-loading strategies).

In the early 1980s, the NRC established geologic repository criteria (10 CFR 60) that include radionuclide containment standards for engineered barriers (here reference is primarily to the waste package and any backfill immediately surrounding the waste package). The requirement is containment for 300 to 1,000 years. The Environmental Protection Agency (EPA) set environmental radiation protection standards for spent fuel disposal (40 CFR 191)[1] for the total repository (engineered and natural barriers within the repository). The Board believes, however, that these should be viewed as minimum standards. The Board expects that a technically sound waste management program would strive to exceed them to enhance safety and increase public confidence.

One approach to achieving such a program might be to design a robust, long-lived waste package that could be shown to have a reasonable assurance of containing radioactive wastes of all forms (solid, liquid, and gaseous) for *thousands* of years. This would give the repository a system of redundant natural *and* engineered barriers to radionuclide release for a much longer period of time. The Board believes that such a multibarrier, defense-in-depth system is the most effective way to improve scientists' ability to confidently predict a repository's performance over long time periods of thousands of years. The Board has recommended repeatedly that the DOE fund

1 *The EPA is revising 40 CFR 191.*

studies and testing of robust, long-lived waste packages.

Of great significance to the design and fabrication of radioactive waste containers is the choice of a thermal-loading strategy for the repository. (See Chapter 3.) And potentially advantageous opportunities could exist if repository thermal loading is shown to be a constructive additional attribute of the engineered barrier system. For instance, it may be desirable to keep the entire repository waste inventory dry for over 10,000 years by "engineering" a relatively high thermal load. Perhaps maintaining consistent conditions at either high or low temperatures will prove most useful for reducing uncertainties about containers lasting "thousands of years." The type of container chosen for emplacement in the repository also will affect to varying degrees many other parts of the waste management system. Research aimed at verifying and optimizing the roles of the various components of the engineered barrier system (including thermal loading) has not yet been carried out. Although this research, which requires time and personnel, is sorely needed, funding in this important area has consistently been cut during the last three years.

At a DOE-sponsored EBS System Concepts Workshop held in June 1991 in Denver, Colorado (discussed in detail in the Board's *Fourth Report*), many waste package design concepts were presented. Some of the concepts covered at the workshop included thick-walled, self-shielding waste packages, nonmetallic containers, increased reliance on geologic analogues, larger capacity waste packages, use of heat pipes, and multibarrier system designs.

During this reporting period, the Board has continued to examine issues pertaining to the engineered barrier system. The potential effects of temperature on the waste package were addressed at a full Board meeting on thermal loading, held in Las Vegas, Nevada, in October 1991. In Chapter 3 of this report, this issue is addressed in detail.

Another Board activity pertaining to the engineered barrier system was a two-day workshop on engineered barriers, which was held in Strasbourg, France, on November 2 to 3, 1991. Sponsored by the Board and the Swedish National Board for Spent Nuclear Fuel (SKN)[2], the workshop's goal was to provide an informal setting in which experts from the United States and several other countries could exchange ideas and experiences about the potential contribution of engineered barriers to their respective programs. More specifically, Board members were interested in hearing what other countries were doing in the area of waste package development. Eighteen participants, representing Belgium, Canada, Finland, Sweden, Switzerland, and the United States, attended this off-the-record workshop. During the workshop, participants identified some of the problems that have arisen in their engineered barrier development programs and discussed approaches that seem to address these problems best.

As a result of the EBS System Concepts Workshop, the workshop in Strasbourg, the Board's ongoing interaction with experts in other programs (see earlier Board reports for details about programs in Canada, Germany, and Sweden), and activities undertaken during this reporting period, the Board is even more convinced that studies of a robust, long-lived waste package should be made a more important part of the DOE's program.

A. Ongoing Board Concerns With the DOE Approach to the Engineered Barrier System

1. The Need to Get Underground as Soon as Possible

The Board has recommended repeatedly that the DOE get underground at Yucca Mountain as soon as possible to assess the character of the complex hydrogeologic features of the area currently under investigation there. Not only is a thorough understanding of the hydrogeology critical to early determination of site suitability, it is also crucial to decisions pertaining to thermal-loading

2 *SKN stands for Statens Kärnbränsle Nämnd. SKN is a Swedish government agency responsible for evaluating and supervising the Swedish nuclear industry's research and development program for the safe management and disposal of spent nuclear fuel. The Swedish parliament recently voted to abolish the SKN as of June 30, 1992, and transfer its functions to other agencies.*

strategy, repository design, waste package design, and other elements in the waste management system.

Early assumptions have been that natural (geologic) barriers would have the capability to isolate radionuclides for very long periods of time. However, drilling and subsurface studies may show that the long-term capabilities of natural geologic barriers to isolate radioactive waste may be more uncertain and harder to predict than some may have supposed. If this turns out to be the case, it is crucial that data be available on the potential contributions of alternative waste package designs and other engineered barriers to overall repository performance.

2. The Current Waste Package Design

The DOE's current waste package is designed to meet minimum regulatory requirements (300 to 1,000 years of "substantially complete containment" according to 10 CFR 60). Concepts being explored by some countries (e.g., Finland and Sweden) provide for a waste package lifetime that is considerably longer than this. No country is working with a waste package goal shorter than the DOE's lifetime goal. The Board has seen nothing to indicate that a waste package lifetime of 10,000 years, and perhaps more, would be unattainable in the U.S. program. However, achieving such a goal with an appropriately high confidence level requires new experimental data, particularly from multi-year experiments. Such experiments must begin soon for results to be ready in time to meet the DOE's current schedule for repository license application in 2001. Although engineered barriers may have shorter lifetimes than do natural geologic barriers, we may be able to predict the performance of engineered barriers with greater confidence than is possible for natural geologic barriers.

3. The Importance of Public Acceptance for Waste Disposal

The credibility and public acceptance of a radioactive waste disposal facility requires that overall system safety be recognized as a primary goal. An engineered barrier system that incorporates robust, long-lived containers may not only strengthen repository performance and safety, but could have the added feature of enhancing credibility and the public's acceptance of a radioactive waste management program. A strongly redundant system of barriers, including robust containers that not only meet, but *exceed*, the minimum regulatory requirements, is a conservative approach that also would lend credence to a program striving to make overall system safety a primary goal.

The DOE's current lack of emphasis on developing and testing long-lived waste packages and other elements of the engineered barrier system may prove to be counterproductive to the goal of building public trust and confidence. Although robust, long-lived containers are likely to be more costly than thin-walled containers, such as the container in the DOE's site-characterization plan (SCP), they could provide overall system cost reductions. For example, costs could be reduced through the use of alternative emplacement modes. A vigorous program of evaluation should be initiated now while system designs are still at a conceptual stage. Renewed emphasis on engineered barriers later in the program may cause the public to believe that such barriers are merely being developed to compensate for deficiencies in the host rock of a potential repository site.

4. Potential Contributions of a Robust Engineered Barrier System to the Overall Waste Management System

The results of an effort to design a redundant, multibarrier system could offer more flexibility to the overall waste management system as it evolves. For example, initial studies of repository configuration by Swedish scientists (KBSII studies) originally contemplated emplacement of waste packages in vertical boreholes in the floors of mined tunnels (similar to the DOE's current strategy). However, for a number of reasons — lower excavation costs, the possible need to be able to retrieve the waste, and increased flexibility to modify the environment — there is a notable shift toward considering drift or room emplacement rather than borehole emplacement. The Board has, in the past, urged the DOE to investigate such alternative emplacement concepts. Robust, long-lived packages, which are also self-shielding, would facilitate the use of drift or room emplacement and could provide direct and simple solutions to other potential safety problems.

5. DOE Budget Allocations to Waste Package R&D

At a January 1992 full Board meeting, DOE officials discussed the fiscal year 1992 budget for the current radioactive waste management program. The 1992 budget allocation to "waste packages" is less than that budgeted for fiscal year 1991 and roughly half of the amounts budgeted for waste packages in 1989 or 1990. The Board is disappointed in the low level of funding planned for this activity (barely 2 percent of the fiscal year 1993 budget request for nuclear waste disposal). The Board is equally concerned about the effect that erratic funding is having on the program's ability to attract and retain top technical talent. Many of the experiments, although of small scale, will run five years and more. Also, justifying new equipment or reserving existing equipment often requires a multi-year commitment, especially when performing research involving radioactive materials.

If the DOE decides to develop a long-lived waste package, the DOE's fiscal year 1992 and proposed 1993 funding allocations for engineered barrier research and development are far from adequate, given the DOE's 2001 target date for application for an NRC license. Even if the pace of the engineered barrier system research program were to pick up soon, there is very little room for error. To meet the existing repository development schedule, the Board estimates that funding levels in the range of $10-15 million annually over the next several years would be necessary to initiate an adequate evaluation of design alternatives for a robust, long-lived waste package.

B. Conclusions

1. Substantial underground excavation is critical to early determination of site suitability. It also is critical for the collection and analysis of data about the isolation potential of the natural (geologic) barrier. However, the DOE has not yet initiated underground excavation of the site at Yucca Mountain, Nevada.

2. It appears to the Board that the DOE's current program in engineered barrier research, as outlined in the SCP, is aimed solely at designing a waste package to meet minimum regulatory standards. The engineered barrier system R&D program should be enhanced, and emphasis should be given to the development of a robust, long-lived waste package.

3. The repository should be based on multibarrier, defense-in-depth principles. Waste packages developed using these principles would exceed, not merely meet, regulatory requirements, thus offering the radioactive waste management program a number of benefits: (1) flexibility to explore alternative repository configurations; (2) avoidance of safety problems that could be experienced during spent fuel transfer and transport; and (3) enhanced scientific and public credibility that the program has made overall near- and long-term system safety a primary goal.

4. There are many potential advantages to developing a robust, long-lived waste package, and the Board has seen nothing to indicate that developing such a waste package is impossible or financially out of reach. However, it is very difficult for the Board to understand how the DOE can permit the engineered barrier program to shrink to such a low level of funding.

C. Recommendations

1. Waste package containment goals should exceed, not just meet, minimum regulatory requirements. To achieve this, the Board again strongly recommends that engineered barriers be viewed as an integral part of the radioactive waste management program, and that development and testing of robust, long-lived waste packages be funded dependably and at a level sufficient to evaluate their contribution to long-term predictions of repository behavior, and to total system safety.

2. The DOE should increase funding to the engineered barrier system program *before* repository-level geologic data become available for the Yucca Mountain site. Increased funding to the engineered barrier system program *after* site-specific geologic data start coming in may be viewed as an attempt to compensate for site deficiencies.

Transportation and Systems

Of particular interest to the Board has been the DOE's progress in incorporating system safety and human factors engineering into the safety management process. This was the subject of recommendations in the Board's first report to the U.S. Congress and the U.S. Secretary of Energy. The first steps taken by the DOE in response to the Board's recommendations in this regard were (1) having a consultant develop a draft system safety program plan, (2) adding specific human factors capabilities to its cask development program, and (3) beginning to incorporate human factors considerations into the design process.

A. The Status of Program Activities Relating to Transportation and Systems

On September 25 and 26, 1991, Board members met with the DOE at the Board's offices in Arlington, Virginia, to review the status of the DOE's program as it relates to transportation and systems issues. Subjects included:

- a status overview of the program and division of resources;
- updates on continuing programs and activities, such as the transportation cask development program, efforts to incorporate system safety and human factors engineering into the safety management process, institutional and outreach programs, operational planning, and shipment tracking;
- status and preliminary results of studies relating to transportation infrastructure at and near utility sites; and
- selected topics, including cask seal testing and the standard contract waste acceptance process.

Notably absent from the DOE presentations on human factors was a plan to generate supporting documents, such as a human factors program requirements document and a human factors design requirements document.

On the second day, the subject of discussions was DOE's systems engineering approach to the waste management process. This was a follow-up to a briefing on this subject that the Board heard at its July 15, 1991, meeting. The discussions focused on several specific questions that members had identified as requiring further elaboration. Two questions of great concern to the Board have been:

1. Will the DOE conduct timely systems engineering trade-off studies, the goal of which would be to optimize (to the fullest extent reasonably achievable) the spent fuel system viewed from start to finish (i.e., from the generation of spent fuel at the utility through final emplacement and beyond)? If it plans such studies, how and when will they be carried out? If it does not plan to do such studies, why not?

2. Given the state of today's waste management system, how will the DOE ensure that the timing of decisions is based upon a thorough understanding of needs, functions, and interfaces — particularly as these decisions involve the acquisition of major systems or systems parts?

The Board believes in the need to perform top-level trade-off studies in a *timely* fashion because they will help synchronize decisions involving the acquisition of major systems or system parts.

During the discussions on the second day, the DOE identified three system trade-off studies under its direction:

1) system throughput rate,

2) monitored retrievable storage issue assessment, and

3) system implications of an above- versus below-boiling repository.

The DOE acknowledged that the studies looked at only parts of the system and that the top-level system trade-off studies need to be done. The DOE now is assembling the "tool box" to enable such studies to be conducted. In the meantime, significant parts of the waste management system are being acquired by both the DOE and individual utilities — by the DOE to meet what it perceives to be a legally mandated 1998 deadline to accept the utilities' spent fuel, and by the utilities to meet emerging needs for on-site dry storage. These acquisitions affect top-level trade-off options and system configuration optimization.

Having a monitored retrievable storage facility ready to accept fuel by 1998 is a goal of paramount importance to the DOE, equal in importance to having a repository operating in 2010. DOE representatives told the Board that procurement actions are under way to acquire current technology shipping casks to ensure that a transportation fleet will be in place by 1998 to begin shipping the spent fuel from utility sites. It should be noted that these soon-to-be-procured casks will be different from those being developed under the "cask development program" referred to above.

The need for additional spent fuel storage capacity, beyond what can be provided by the spent fuel pools, has emerged at a number of reactor sites. According to the Nuclear Regulatory Commission, by the end of 1991, eight utilities had either dry storage facilities in place or had submitted license applications for constructing such facilities. These storage capabilities are being supplied by different vendors using different technologies; some, for example, will use metal casks, and others will use a concrete vault arrangement.

The more we do now to acquire elements in the waste management system, the less flexibility is left in the system for optimization. System studies should be completed *before* a serious loss takes place in overall system flexibility.

B. Conclusions

1. The Board is encouraged by the progress the DOE has made in its transportation planning and management efforts to incorporate system safety and human factors engineering. The Board will continue to encourage the DOE to develop the support documents necessary for the implementation of these programs. The DOE should include these disciplines in its systemwide safety management process.

2. With respect to managing the entire waste program from a systems approach, the Board remains concerned about the need to perform top-level trade-off studies in a *timely* fashion, so that the results can be synchronized with major decisions involving the acquisition of major systems or system parts.

3. The Board believes that the major components of the waste management system — storage, transportation, and disposal — are strongly interconnected. A decision on the design configuration of one component may have significant effects on the configurations of the other components, and, thus, the entire system. The concern is that decisions and acquisitions are being made that are incrementally locking in elements of the system — by the DOE to meet mandated deadlines and by the utilities, acting individually, to meet emerging fuel storage requirements. The issue is how to avoid a process that locks in the waste management system configuration before the merits of possible alternatives have been properly evaluated.

C. Recommendations

1. The Board recommends that the DOE initiate and pursue vigorously top-level system trade-off studies so as to provide a firm, systemwide rationale for making the various major decisions that will affect the safety, efficiency, and design of the total waste management system.

2. The Board recommends that the DOE develop the necessary supporting documents for the implementation of system safety and human factors programs, including program plan and design requirements for human factors, as well as overall system safety.

Chapter 3

Thermal Loading of a High-Level Radioactive Waste Repository

Approximately 20 percent of the nation's electric power is generated by nuclear reactors located at about 70 sites around the country (Leigh and Patridge 1991). These commercial reactors produce electricity by burning, or fissioning, enriched levels of uranium. The uranium is formed into fuel pellets that are placed in long, thin, zircaloy tubes. These "fuel rods" are assembled into bundles called fuel assemblies. The heat generated during this fission-ing process is used to produce steam, which in turn generates electric energy. After three or four years in a reactor, the fuel becomes less efficient in sustaining the fission process. The "spent fuel assemblies" are then removed and replaced with new fuel assemblies. Spent fuel is placed in water pools at the utilities to cool.

Spent fuel assemblies continue to produce substantial amounts of radioactivity and thermal energy as the radionuclides decay. The radioactive emissions are hazardous, and significant unprotected exposure can cause sickness in and death to humans. The only way to protect the public health and the environment is to isolate the radioactive material from the accessible environment. Some radioactive materials decay rapidly. For example, the fission products strontium-90 and cesium-137 have half-lives[1] of about 30 years. Others decay much more slowly: Plutonium has a half-life of about 25,000 years, requiring isolation from the accessible environment for thousands of years.

The amount of thermal energy produced by spent fuel depends on many things, for example, how long it was irradiated in the reactor and how long it has been aged in pool or dry storage.

Spent fuel will continue to produce thermal energy after disposal in a geologic repository. Scientists must therefore determine how elevated temperatures will affect the waste packages and the rock surrounding the waste packages, and decide what the temperature limits should be for the various components of the repository. Once this has been determined, a repository can be designed to achieve the desired range of temperatures over a chosen period of time. Deciding on a way to achieve these temperatures over the chosen time period is referred to as a "thermal-loading strategy" for the repository.

As indicated above, the *thermal load* of a repository (in kilowatts per acre) can be controlled or manipulated. A number of factors affect the *thermal load* of a repository. For example,

- The burnup history of the spent fuel (e.g., how long the spent fuel remains in the reactor). The higher the burnup, the higher the thermal output. The burnup level is controlled at the individual reactor sites.
- The age of the spent fuel (measured in years since removal from the reactor). Young spent fuel has a high initial thermal output.

1 *The time required for a radioactive substance to lose 50 percent of its activity by decay.*

- The amount of spent fuel placed in each waste package.

- The number of packages emplaced per acre.

- How the packages are emplaced (e.g., in boreholes or in drifts).

The *temperatures* in a backfilled geologic repository are a direct result of primarily two factors:

- The thermal load of emplaced waste (in kilowatts / acre) and

- The thermal conductivity of the repository — primarily the rock. Given the same thermal load, the higher the conductivity of the repository rock, the lower the repository temperature.

Temperature levels within the repository also can be controlled over time to some degree through the use of enhancements to the repository, such as heat pipes or other heat transfer devices. However, the key controlling factors pertain to the condition, packaging, and emplacement of the spent fuel.

The choice of a thermal-loading strategy is a key decision in the waste management system. It will influence all aspects of the system, including, for example, if and how long the spent fuel should be aged, the size and design of the repository, and the design of the waste package. The thermal-loading strategy also could significantly affect the handling, storage, and transport aspects, as well as the costs of the waste management system.

Because the Board originally had identified thermal loading as having wide-ranging implications for the entire waste management system (NWTRB, March 1990), it decided to look into the issues related to thermal loading at a Board meeting in October 1991. The Board was interested in hearing about the history and origins of the DOE's baseline thermal-loading strategy as well as from experts in disposal programs in Canada, Germany, and Sweden. Although these countries are evaluating waste disposal in geologic media and hydrologic settings different from the candidate site for the U. S. program, they are facing similar uncertainties as they design their respective systems.

The Meeting on Thermal Loading

The major purpose of the October 1991 meeting was to review the rationale and effects of various thermal-loading strategies as they relate to the design and performance of a high-level waste repository. Specific emphasis was placed on the candidate site at Yucca Mountain, Nevada, which currently is the only site in the United States undergoing characterization for its potential suitability as the location for a geologic repository.

The meeting started with a keynote presentation entitled "Strategic Implications of Heat in a High-Level Radioactive Waste Repository." This was followed by a review of the proposed concepts and rationales behind the Canadian, German, and Swedish high-level waste management systems. A corresponding review was presented on the evolution and rationale leading to the present U.S. conceptual design proposed for Yucca Mountain, Nevada. Sessions held the second day addressed technical uncertainties, enhancements, and other considerations associated with alternative thermal-loading strategies. The sessions held on the third day addressed the implications of alternative thermal-loading strategies. The final afternoon session was structured to encourage an open discussion of the preceding sessions.

The next few sections of this report outline the thermal-loading baseline strategy for the Yucca Mountain site, as presented by the DOE at the meeting. Alternative strategies, including those being evaluated in Canada, Germany, and Sweden are reviewed. Then, technical issues and uncertainties relating to thermal loading of a repository are reviewed. Finally, Chapter 4 discusses the systemwide implications of thermal loading, ending with conclusions and recommendations.

Thermal-Loading Strategies (U.S. and Others)

The repository conceptual design and baseline thermal-loading strategy presented to the Board by the DOE is an adaptation of the design first published by the DOE in 1987 in its Site Characterization Plan - Conceptual Design Report (SCP-CDR) for the

Yucca Mountain site. In addition to describing the repository conceptual design and operations, the SCP-CDR summarizes the design bases, the design and performance criteria, and the design analyses. It also documents the status of the repository design effort as of September 1986.

Major portions of the SCP-CDR were incorporated into the SCP, which was published by the DOE in 1988. The purpose of the SCP is to describe in detail the activities the DOE has planned as part of its program to characterize the geologic, hydrologic, and other conditions of the site relevant for determining the suitability of Yucca Mountain for a repository. Its purpose is also to ensure that data-gathering plans are appropriate to support the design and licensing of the repository system (DOE, SCP 1988).

The DOE's presentation at the October meeting indicated, and a review of some of the pertinent documents in the evolution of the U.S. high-level waste program seems to confirm, that high thermal loads and above-boiling temperatures for relatively short time periods (several hundred years) have been assumed in most discussions of potential repository concepts since 1957 — in *both* saturated and unsaturated environments. Several media, including salt, basalt, granite, shale, and finally tuff have been considered over the years; however, until 1983, the prevailing view seems to have been that young (i.e., 10 years old) spent fuel would be placed in saturated geologies (below the water table) at thermal loadings that would drive near-field rock temperatures well above the boiling point of water. Table 3.1 lists some of the key documents in the technical evolution of the U.S. program.

One of the first reports to focus on uncertainties introduced by high thermal loads is a 1978 report by the U.S. Geological Survey (USGS). This report recognized that "...given the current state of our knowledge, the uncertainties associated with hot wastes that interact chemically and mechanically with the rock and fluid system appear very high." The report further concludes: "The uncertainties connected with all these media are greatly reduced if the media are used, at least initially, only for relatively cool waste (surface temperatures < 100°C)." A 1983 USGS report echoed concerns about complications that can be attributed to high thermal loads. Finally, the NRC in 1983 established in 10 CFR 60 a 300-to-1,000-year waste package containment requirement. In the accompanying statements of consideration, the NRC expressed its concern that "thermal disturbances of the area near the emplaced waste add significantly to the uncertainties in the calculation of the transport of the radionuclides through the geologic environment." A review of the literature has not uncovered any substantial body of work intended to resolve or reduce the uncertainties associated with high thermal loads. These uncertainties persist today.

The heat given off by high-level radioactive waste is a major consideration in any strategy for waste isolation in a repository. All hypothetical thermal-loading strategies may be characterized initially as either "above boiling" or "below boiling." (All above-boiling conditions will eventually reach below-boiling temperatures.) As already mentioned, the temperatures that will be experienced by the natural and engineered barriers in a repository can be predicted and controlled to a large degree by manipulating variables such as the contents, ageing, and spacing of waste packages. As a result, it is possible to compare several thermal-loading strategies in an attempt to choose one that best assures long-term safety in light of existing uncertainties associated with long-term waste isolation.

The DOE's current (above-boiling) baseline strategy appears to have evolved during the 1980s not as a result of such a comparative analysis, but rather as a result of the examination of a variety of thermal criteria, which consistently supported the assumption that relatively young spent fuel (i.e., 10 years old) would be emplaced and that temperatures in the repository would remain above boiling for a relatively short (several hundred years) period of time. So far, however, a comprehensive examination of the advantages and disadvantages of alternative thermal-loading strategies (e.g., below boiling, or above boiling for several thousands of years) in various media — or at least in tuff — has not yet been undertaken. Recently the Board was told that under the oversight of the management and operations contractor a systems analysis would be performed that planned to consider several thermal-loading

Table 3.1 — Key Documents in the Technical Evolution of the U.S. High-Level Waste Management Program

Date	Organization	Findings/Actions
1957	National Academy of Sciences (NAS)	Committee on Waste Disposal recommends disposal in openings excavated in salt beds and salt domes as most promising for many reasons including advantages of comparatively high thermal conductivity. Above-boiling concept first postulated (NAS 1957).
1974	Atomic Energy Commission (AEC)	Draft Environmental Statement briefly discusses the general thermal effects associated with the disposal of high-level waste in a pilot-scale geologic repository in salt (AEC 1974).
1974	Isaac J. Winograd (U.S. Geological Survey - USGS)	Discusses the merits of siting a shallow repository above the saturated zone in the arid Western U.S. Lists difficulty of evaluating heat-related stresses as a liability (Winograd 1974).
1978	USGS	Publishes circular on earth-science perspectives of geologic disposal. Discusses uncertainties associated with high rock temperatures (USGS 1978).*
1978	National Research Council, Committee on Radioactive Waste Management	Panel on Hanford Wastes suggests high-level defense waste repositories at Hanford be located in unsaturated zone of Rattlesnake Hills. Also suggests ventilation by passive air circulation (NRC, Hanford 1978).
1978	National Research Council, Committee on Radioactive Waste Management	Panel on Geological Site Criteria recommends that repository temperature be kept low enough to avoid adverse physio-chemical reactions in the host rock (NRC 1978).
1979	Interagency Review Group on Nuclear Waste Management	Briefly suggests using lower thermal loads as a conservative approach to repository development (IRG 1979).
1980	Department of Energy (DOE)	Issues *Final Environmental Impact Statement* on management of commercial radioactive waste. Reports on thermal and thermal mechanical analyses undertaken (for bedded salt, granite, shale, and basalt) to determine maximum acceptable thermal-loading values (APDs). See especially Appendix K (DOE 1980).
1980	DOE – Office of Nuclear Waste Isolation	Presentation at 1980 National Waste Terminal Storage Program Information Meeting updates activities of the RRC-IWG, which is developing generic criteria for "far-field." Limits repository APD to 100 kW/acre for tuff; host-rock near-field temperatures not to exceed 215°C for tuff (all candidate sites still in saturated zone). Identified preliminary technical limits for siting repository in saturated tuff (DOE-ONWI 1980).
1982	DOE – National Waste Terminal Storage Program	In its program criteria, states that "limiting the impacts of heat generated by the waste is a principal consideration in the design of a repository" (DOE-NWTS 1982).
1982	USGS	Writes letter that concludes that conditions present in the unsaturated zone beneath Yucca Mountain should provide a favorable environment for a repository (Robertson et al. 1982).
1983	USGS	Publishes circular that reviews merits of disposing of high-level waste above the water table in arid regions. Lists groundwater and heat as the "primary concerns in any repository" (USGS 1983).
1983	National Research Council, Board on Radioactive Waste Management	Waste Isolation Systems Panel issues report saying volcanic tuff above the water table is better medium to provide time delays for potentially contaminated ground water to travel off-site than is saturated tuff (NRC 1983).
1983	10 CFR 60	Nuclear Regulatory Commission establishes a 300-to-1,000-year waste package minimum containment requirement. Expresses concern about "thermal disturbances." (See also NRC 1990.)
1985	Sandia National Laboratories	Technical correspondence supporting the *Final Environmental Assessment* provides preliminary temperature profiles for the disposal of spent fuel at Yucca Mountain for a thermal loading of 57 kW/acre (Sandia 1985).
1986	DOE	As part of environmental assessment, designates single panel, 1,260 (now 1,520) acres, at depth of 390 meters below surface (170m above water table) with 57 kW APD (DOE 1986).
1987	Sandia National Laboratories	Publishes SCP-CDR; includes description of geologic repository. Documents design effort as of 1986 (Sandia 1987).
1988	DOE	Publishes SCP (most recent official definition of site-characterization program and repository system concept). Includes 1986 design criteria (DOE 1988).

* *The report refers to merits of high sorptive potential of zeolitized tuff for radionuclides and cautions that high thermal loads could adversely affect this desirable feature. Repeats 1974 suggestion by Winograd that unsaturated zones of the arid Western United States should be considered for siting a repository. Also states that geologic uncertainties could be offset in part by the adoption of a "multiple-barrier" or "defense-in-depth" repository design to assure long-term radionuclide containment.*

strategies. The Board believes that such an effort is overdue.

A. The Current U.S. Baseline Thermal-Loading Strategy

Simply stated, the current U.S. baseline thermal-loading strategy calls for above-boiling temperatures in the immediate vicinity of the waste packages for approximately 300 to 1,000 years after permanent repository closure, followed by below-boiling temperatures.

The geology of the portions of Yucca Mountain being characterized for suitability for locating a repository consists of tuffaceous rock (consolidated volcanic ash) located in an unsaturated zone that is as much as 760 meter thick.

Should the waste containers in a repository be breached, the most likely pathway for nongaseous radionuclides to the accessible environment is thought to be ground water.[2] It is thought that locating the repository in an unsaturated zone will result in increased confidence that liquid water will be kept away from waste containers for a period of time, thus preventing, or greatly retarding, aqueous corrosion of the containers for that period. In addition, scientists believe that maintaining temperatures above the boiling point of water around the containers will help keep the containers dry, thus retarding further aqueous corrosion.

The DOE's current baseline strategy is based on the following repository configuration concept, presented to the Board at the October meeting.

Waste and Waste Package Parameters

- Each spent fuel waste package would contain four boiling water reactor and three pressurized water reactor fuel assemblies (i.e., a hybrid, intact configuration).
- A "levelized" spent fuel receipt scenario starting in 2010 is planned, where younger and older fuel assemblies are mixed and matched to achieve some degree of uniformity among the heat generation rates of the waste packages.
- Defense high-level waste[3] containers would be commingled with spent-fuel canisters and would have an initial power output of .2 kilowatts/container.
- An engineered barrier system would provide "substantially complete containment" for 300 to 1,000 years (a requirement of NRC regulation 10 CFR 60).
- The yearly release rate of any radionuclide from the engineered barrier system would not be greater than one part in 100,000 of the inventory of that radionuclide calculated to be present 1,000 years after permanent repository closure (a requirement of 10 CFR 60).

Repository Parameters and Requirements

- The repository would be located approximately 300 meters below the eastern flank of Yucca Mountain. It would occupy approximately 1,520 acres and contain approximately 100 miles of underground tunnels.
- The congressionally mandated limit of 70,000 metric tons of spent fuel and high-level waste would be accommodated in the 1,520-acre Yucca Mountain repository block.[4]
- Waste packages would be placed in vertical boreholes in the floors of drifts. Spacing between drift centerlines would be 16 meters; variable borehole

2 *Gaseous releases, however, do not require the presence of liquid water.*

3 *The responsibility to determine whether there is a need for a separate repository for defense high-level waste from reprocessing was given to the President. In 1985, the President decided to place both spent nuclear fuel and defense high-level waste in the same repository.*

4 *Congress limited the total amount of high-level nuclear waste that could be placed in the first repository to 70,000 metric tons of heavy metal, which would consist of approximately 63,000 metric tons of heavy metal from spent fuel in approximately 31,000 waste packages and 7,000 metric tons of heavy metal from defense high-level waste in approximately 15,000 waste packages.*

spacing would be used depending on the thermal load of the individual packages.

- The repository will remain open to permit retrieval of the emplaced waste packages for 50 years following initial emplacement (a requirement of 10 CFR 60).

- Areal power density (APD), a measure of thermal loading, at the time of emplacement would be approximately 57 kilowatts / acre.

- The repository system must isolate the radionuclides from the accessible environment effectively for 10,000 years (a requirement of EPA standard 40 CFR 191).

Given the above parameters, the temperature of the host rock adjacent to the waste package would exceed the boiling point of water shortly after emplacement and remain above the boiling point of water for a period of 300 to 1,000 years. The temperature would then fall below boiling. The basic idea behind the DOE's baseline strategy is to create a hot / dry environment for the waste packages. An above-boiling temperature around the waste packages would be achieved by adjusting the contents of each package and spacing the boreholes at specific distances. The desired APD (57 kilowatts / acre) was calculated to ensure that the centerline temperature of the waste package would not exceed 350°C. This results in a maximum wall rock temperature of 275°C (i.e., a thermal limit) and 200°C one meter from the borehole wall within the host rock.

According to this concept, the above-boiling temperatures would drive away any moisture that might otherwise reach the containers. This, in theory, should prevent, or at least greatly retard, aqueous corrosion of the containers for at least 300 years. How the host rock will actually perform under these high temperature conditions has yet to be tested and validated.

Several general characteristics associated with the U.S. baseline thermal-loading strategy require consideration:

1. There would be two thermal regimes along with their associated uncertainties: above-boiling for a period of 300 to 1,000 years and below-boiling for the period thereafter.

2. This DOE baseline strategy — incorporating relatively short-lived containers — relies on geologic barriers to isolate the radionuclides beyond the 300-to-1,000-year period.

3. Both the technical and nontechnical communities could perceive the current above-boiling strategy as entailing greater uncertainties with regard to geotechnical, hydrologic, and geochemical aspects than a below-boiling strategy because many conceptual aspects associated with above-boiling conditions have yet to be tested and validated.

4. Also, this strategy, involving young spent fuel, requires substantial hot-cell fuel handling to obtain the appropriate mixtures of burnup and age. The attendant uncertainties in human factors, seismic and other risks, as well as system costs must be recognized.

These general characteristics and the uncertainties associated with them are discussed in Chapter 4.

Schedule

DOE repository target dates, whether contractually, legislatively, or self-imposed, may prove to be optimistic given the uncertainties associated with such a first-of-a-kind program that must withstand intense public scrutiny. For example:

- The Nuclear Waste Policy Act of 1982 (NWPA) set forth an anticipated date for the DOE to initiate disposal of spent fuel or high-level waste of not later than January 31, 1998.

- In 1989 in its report to Congress, the DOE (although recognizing the difficulty of meeting the January 31, 1998, date) retained 1998 for *receiving* spent fuel from the utilities at a monitored retrievable storage facility but refocused the repository program on two target dates: October 2001 for submission of a repository license application to the NRC and the year 2010 for beginning repository operations (DOE 1989).

Although not of a technical nature, these target dates have in many cases and to varying degrees affected technical and programmatic decisions. For example, the 1998 date contained in both the NWPA and the standard DOE spent fuel disposal contract with the utilities has given the DOE's program an element of schedule urgency which is not present in the nuclear waste programs of other nations. This sense of urgency may have significantly influenced the DOE's early choice of a high thermal-loading baseline strategy. The literature confirms the consistent assumption that relatively young spent fuel (i.e., 10 years and older) would be emplaced in a repository.

B. Alternatives to the Current U.S. Baseline Strategy

Long-Term Above-Boiling Strategy

There are other thermal-loading strategies with very different underlying rationales. One presented at the Board's October meeting as an alternative to the U.S. strategy is a long-term above-boiling strategy.[5] It is based on the same unproven theory as the U.S. baseline strategy — keeping moisture away from the waste package will prevent aqueous corrosion and transport of nongaseous radionuclides. Basically, the long-term above-boiling strategy postulates that if it proves beneficial to keep moisture away from the waste package for 300 to 1,000 years, why not keep the waste at above boiling temperatures for 10,000 years?

The initial very high rate of heat generation of young spent fuel (see Figure 3.1) decreases significantly during the first 60 or so years of ageing — although it still remains highly radioactive. If the waste is aged for 60 or more years, with the correct repository loading configuration, rock temperatures near the waste packages would remain above boiling for periods in excess of 10,000 years. According to this strategy, moisture would be kept away from the waste packages for 10,000 years or more, exceeding the 300-to-1,000-year minimum containment period and extending protection to cover the 10,000-year period required in 40 CFR 191.

Some implications that this strategy may have for the system as a whole include:

- The 1,520-acre repository planned for Yucca Mountain could accommodate spent fuel in excess of 150,000 metric tons, possibly eliminating the need for a second repository site, or at least postponing its need for several decades.

- To reduce the high initial temperatures and maintain above-boiling conditions, the spent fuel would have to be aged for approximately 60 years before final emplacement, and packed more densely in the repository.[6]

- Like the current U.S. baseline strategy, the long-term above-boiling strategy could be perceived by the technical and nontechnical communities as entailing more uncertainties than the below-boiling strategy.

Below-Boiling Strategy

Another strategy deserving consideration is the below-boiling strategy, where temperatures in the host rock never rise above the boiling point of water. Figure 3.2 graphically depicts the U.S. baseline thermal-loading strategy together with a long-term above-boiling strategy and a below-boiling strategy. The below-boiling strategy does not rely on a thermal shield to protect the waste package from liquid water. In return, however, the below-boiling strategy gives a temperature regime, where rock properties and behaviors *may be* more predictable; it also reduces stresses within the host rock from thermal expansion.

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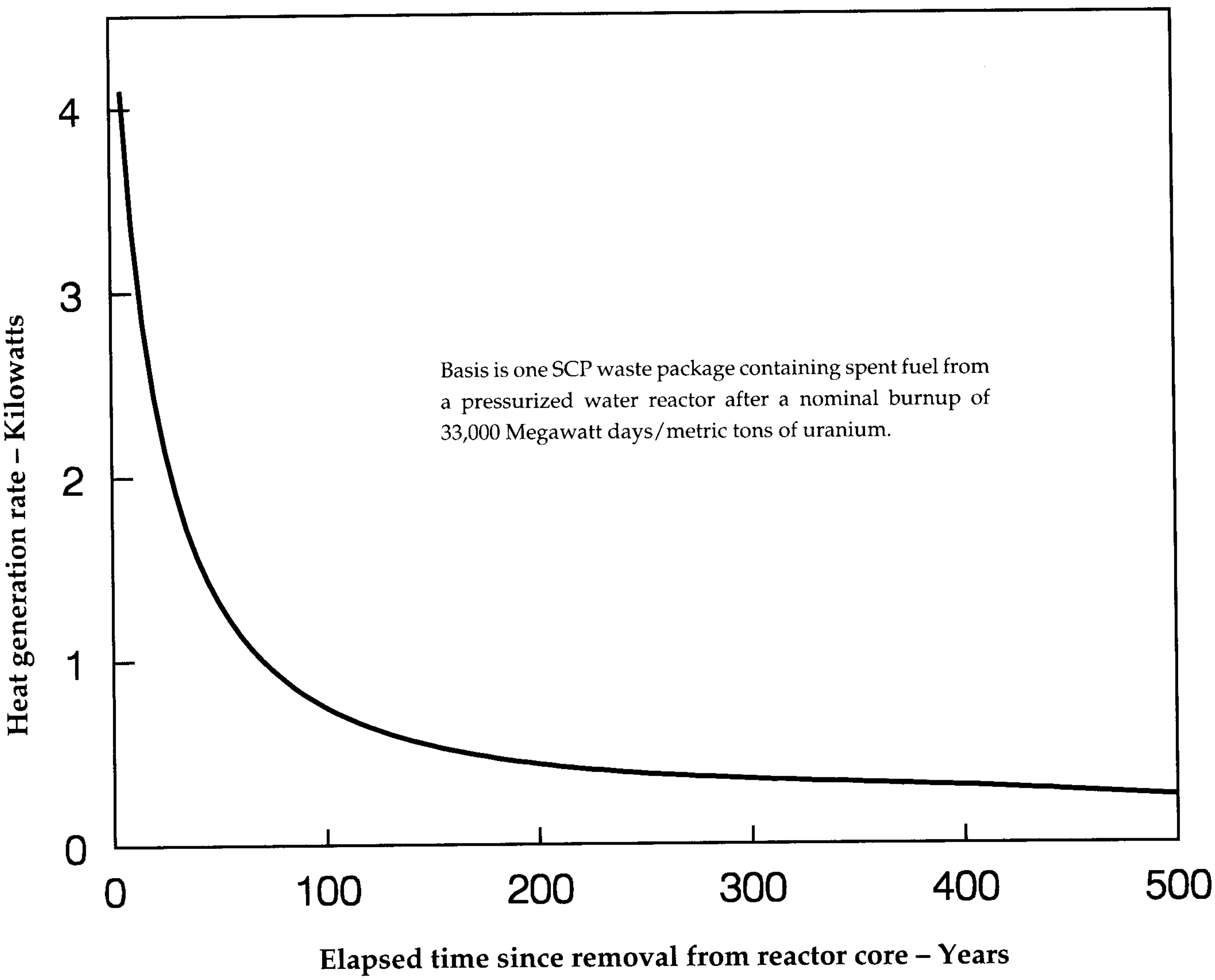
5 *Ramspott, L. "Strategic Implications of Heat in a High-Level Radioactive Waste Repository." Lawrence Livermore National Laboratory, as presented to the Board October 8, 1991.*

6 *A number of ways for accomplishing the ageing are evident: storage near the reactors in dry casks, storage at a facility equivalent to a monitored retrievable storage facility, storage in the repository prior to closure, and combinations of these and other options. Cooling, generally with ambient air, ideally would be required during storage. The optimum mix of ageing methods would be selected based on a comprehensive systems study.*

Figure 3.1 — Spent Fuel Heat Generation Rate



The thermal output of spent fuel decreases significantly over time, especially during the first several decades.

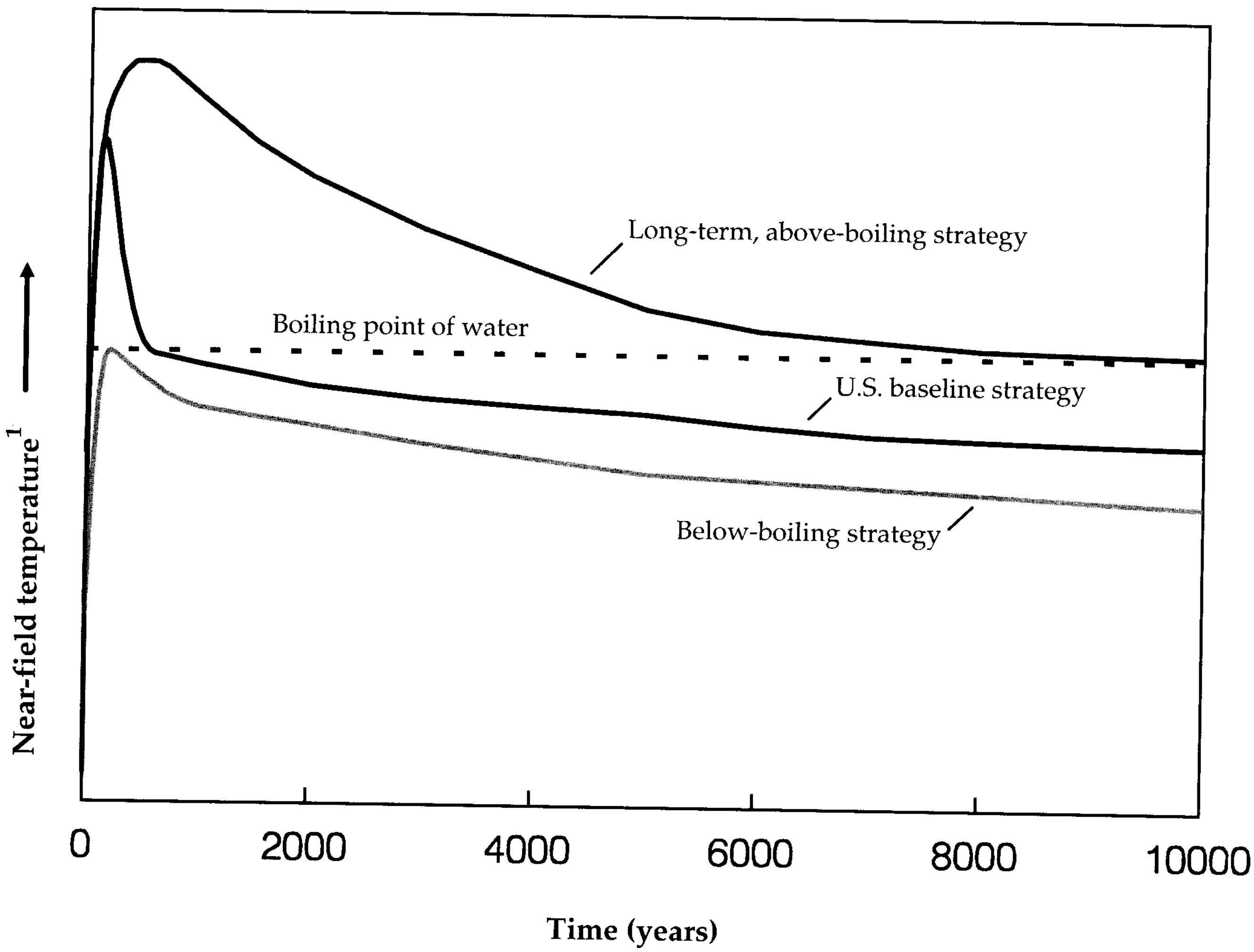
Adapted from presentation to the Board by L. Ramspott on October 8, 1991

The below-boiling strategy can be achieved by a combination of spent fuel ageing, placing less waste in each package, and/or wider spacing of waste packages in the repository. A potential disadvantage of this strategy could be a reduction in the ultimate capacity of a repository or the need for more repository area outside the currently envisioned 1,520 acres. Because temperatures are below boiling, materials such as bentonite, a natural clay, could be used to surround the waste containers. Properly placed, bentonite is virtually impervious to water. However, bentonite may lose its sorptive properties and impermeability if long-term temperatures remain slightly above boiling.

C. Strategies Being Evaluated in Other Programs

Geologic repositories for high-level waste disposal have yet to be built anywhere in the world, and only the U.S. program is evaluating the suitability of tuff in an unsaturated geology at this time. Nonetheless,

Figure 3.2 — Three Thermal-Loading Strategies



[1] Temperature in the host rock zone within a few meters of the waste package

The U.S. baseline strategy is the only strategy that combines above-boiling and below-boiling temperatures during the first 10,000 years.

Adapted from presentation to the Board by T. Buscheck, E. Ryder, and L. Ramspott on October 8 and 9, 1991

the United States can benefit from some of the experience gained as other nations design and plan their programs. Experts from the Canadian, German, and Swedish programs participated in the October Board meeting to provide insight on their current thermal-loading strategies, as well as to offer any insight on the U.S. program.

Canada

The Canadians envision redundant natural (granite) and engineered barriers. Canada is not yet looking at a specific site, but is investigating and developing a *concept* for spent fuel disposal in the granitic rock of the Canadian Shield, which extends over large portions of eastern and central Canada. Under current plans, the repository would be excavated about

1,000 meters underground in granite in the saturated zone. An underground research laboratory for studying the viability of geologic disposal in such an environment is located at Pinawa, Manitoba.

The Canadians are considering a below-boiling strategy for three major reasons. First, they believe low temperatures will retard corrosion of the container. Current work on container materials is focused on two grades of titanium and oxygen-free copper. (Researchers in Canada also are considering the design and development of containers that will last for at least 500 years, as well as multipurpose casks that can be used for storage and transport to minimize handling.)

Second, they plan to surround the waste package with a mixture of sodium bentonite clay and silica sand. Low thermal loading is desirable so as not to compromise the swelling qualities of the bentonite buffer. Bentonite can slowly convert to the less-sorptive clay illite in the presence of potassium ions, and loses its swelling properties and imperviousness above 100°C.

Third, they also believe low temperatures will minimize the opening of fractures in the host granite or the propagation of existing fractures to greater depth.

The Canadians, who have as much spent fuel as the United States, believe it can be stored safely at their few reactor sites for many decades. Disposal is not expected to begin before 2025, and provisions for extensive technical and public review have been built into the concept development process.

Sweden

Many aspects of the Swedish program are similar to those of the Canadian program. Swedish scientists are looking at spent fuel disposal in granite in the saturated zone. They have not yet begun to characterize a site but have been performing research in comparable environments underground. They envision a low thermal-loading strategy (below 100°C), plan to age the spent fuel before disposal for at least 40 years, and are investigating the advantages of bentonite sealing around the waste packages.

The Swedish program has opted for a very long-lived waste container. After considerable research and design work, the latest design calls for heavy containers made of copper and steel. Swedish researchers believe such containers may have lifetimes of upwards of a million years in the environment under consideration. The buffer material around the container is proposed to be compacted bentonite, which swells when soaked by ground water, thus preventing further permeation of ground water to the container surface. The most important technical reason behind Sweden's low thermal-loading rationale is to be able to use bentonite as a backfill or buffer system.

Germany

The German program to dispose of spent fuel is quite different from the Canadian, Swedish, and U.S. programs in several ways. The Germans are evaluating the disposal of spent fuel in salt domes, in which the salt would flow into and around the waste, sealing it off completely from the accessible environment. Although their strategy involves high thermal loading, they must limit the temperatures to 200°C to prevent chemical alteration of the salt. The Germans envision long-term storage of spent fuel at a centralized facility but have no regulatory acceptance requirements.

In determining its thermal-loading rationale, Germany has faced a number of different issues. First, German spent fuel still is being reprocessed although the current German government may decide to discontinue this procedure. The nominal heat output for a container of vitrified high-level waste from processing is 2.3 kilowatts. Intermediate-level wastes reach up to about 100 watts per container. All types of waste will be disposed of in their underground repository. Another issue is that — unlike in the United States — there is no requirement to retrieve the waste. In fact, due to the slow creep of salt, the waste will be "self-sealed" inside the salt. A third issue is the complex stratigraphy of the German salt domes. As more is learned about this stratigraphy, the thermal-loading rationale may change.[7]

Summary

The Canadian, German, and Swedish programs are all still in the early stages of planning, site characterization, and research. Currently, the programs differ considerably from the U.S. approach in terms of repository geology, hydrology, and thermal-loading strategy, as well as in other aspects. For example, in all three countries ageing has been built into the system design. Also, despite the early stages of their program development, all three countries are currently performing research underground in the media they are proposing for repository development. Finally, contrary to the U.S. situation where schedules are given high priority, neither Canada, Germany, nor Sweden envisions permanent disposal at a site before 2025.

Technical Issues and Uncertainties

During its October meeting, the Board asked that the technical uncertainties associated with alternative thermal-loading strategies be presented. The following is a discussion of the issues raised during the meeting. Systemwide issues are discussed in Chapter 4.

A. Geotechnical Issues and Uncertainties

The repository design concept for Yucca Mountain offers no unique geotechnical challenges for below-boiling thermal-loading strategies. Considerable industry experience exists for the engineering and construction of large, complex, underground facilities. The U.S. underground construction industry has, over recent years, completed approximately $1 billion worth of underground facilities for U.S. civil projects annually. At the Nevada Test Site approximately 50 miles of tunnels and unique underground openings have been excavated in tuff over the last 30 years in support of the U.S. nuclear weapons testing program.

The DOE has proposed an above-boiling repository for its baseline design concept. If the maximum dimensions of the underground openings are held to a reasonable limit and care is taken in the design and excavation of the openings (particularly at merges and intersections), temperatures associated with the proposed above-boiling concept should have little impact on the long-term structural stability of the repository.

The long-term stability of an underground opening is dependent on two factors: the size of the opening and the quality of the rock excavated. The smaller the opening, the greater the intrinsic stability; the better the rock quality, the less structural support is required. Hence, in seeking the least uncertainty for long-term stability, maximum dimensions of openings should be as modest as possible, allowing structural support to offset natural variations in rock quality.

There are, however, issues and uncertainties related to the near-field thermal-mechanical response of the host rock at elevated temperatures. Because there is no sharp phenomenological difference in geomechanics between the above- and below-boiling temperature regimes, the format for the following discussion is not broken out by thermal-loading strategy.[8]

7 *Scientists know, for example, that polyhalite, a major component of salt domes, starts to decompose at 230°C; therefore, maximum temperatures would have to be limited to 200°C. Even more sensitive to temperature is the mineral carnallite, present in some of the strata of the German salt domes. The water release temperature at ambient rock pressure starts at 85°C, but increases dramatically with rock pressure. With rock pressure of about 100 Bar, a temperature release limit of 145°C is calculated. This means the temperature would have to be limited in the rock salt by placing containers at proper distances between the rock itself and any carnallitic seam. At the same time, the temperature would have to be kept as high as possible because heat accelerates creep in the salt, which then entombs the waste.*

8 *The material in this section is drawn largely from the presentations made by T. Blejwas on "Repository Design Considerations," and L. Costin on "Geomechanical Uncertainties" at the Board's October 8-10, 1991, meeting, and from related discussions.*

Issues

1. The effect of heating on the intact rock modulus (Young's modulus) and permeability will depend upon the confinement of the rock and the level of the resultant shear stress. Near the surface of openings and boreholes, confinement is low and stress differences are high. Heating will tend to increase tangential and shear stresses. If these increases in stress approach the strength of the intact rock, new fractures will form and existing fractures will tend to open. As a result, the rock modulus will decrease and fracture permeability will increase.

Away from the surface of the openings where confined conditions dominate, heating increases the compressive stress in the rock, which tends to close fractures, decrease fracture permeability, and increase the rock modulus. These changes may be small if the natural fractures in the rock are tight and undisturbed.

2. Thermal loading of jointed rock that has been excavated will produce greater changes in the rock modulus and permeability than would occur in undisturbed rock. Thus, care must be taken in using laboratory data or conducting in-situ tests where the rock has been disturbed.

3. Stresses due to heating could produce extension fractures parallel to and on the order of a tenth of a radius of the opening behind the excavated surfaces. Unstable "stress slabs" can then form, depending on the ratio of rock strength to the rock modulus as well as temperature gradients.

Stress slabbing can occur around openings due to overburden stresses alone. These effects are quite prominent around openings excavated in the weak, nonwelded tuffs of G tunnel at the Nevada Test Site, which is at a depth of 300 meters. Stress slabbing will be less pronounced in the higher strength, fractured welded tuffs anticipated at the proposed repository level because the tuff strength is high with respect to the overburden and thermal stresses, and because movements along the natural fractures in the rock will tend to relieve thermal stresses.

4. Upon excavation of openings in the welded tuffs at the repository level, some loosening of the near-surface rock will take place, resulting in a lower initial rock modulus. As a result, subsequent heating will produce smaller increases in tangential stresses near the surface of the openings.

Formation of new fractures and stress slabbing around openings does not mean that they must remain unstable. Such openings will remain stable if early structural support is installed to hold the fractured rock in place.

5. Drying of the rock, as a result of heating or ventilation, can result in increased brittleness, decreased volume, and the formation of shrinkage cracks. The effect of drying due to exposure and ventilation is quite pronounced in the nonwelded tuffs in openings excavated in G tunnel. Until the surface of the tuff could be covered with shotcrete, new fractures developed and slabs tended to form and continued to loosen between rock-bolt supports. Such effects will be more pronounced in high water content nonwelded tuffs and less prominent in the lower porosity welded tuffs.

6. Some percentage of the proposed waste emplacement boreholes could have slabs that develop and loosen and impinge upon the emplaced waste container. The loss of the air gap around portions of some of the containers should be assumed as an uncertainty for this proposed configuration. A system for removal of the waste container from the vertical boreholes during the retrieval period should be capable of excavating around such containers. Different waste emplacement concepts or use of borehole liners should be considered as alternatives to the proposed concept.

7. Numerical models are useful for evaluating stress and thermal conditions around openings, but they, alone, do not provide a means of assessing failure mechanisms. Much of the needed data on rock characteristics will come from careful observations of fracturing and deformations in the excavated openings through well-coordinated mapping and construction monitoring activities. Insights can be obtained from lab testing, but they should be calibrated against field observations. Careful mapping and observation of rock behavior during excavation of the exploratory studies facility are essential to

reduce uncertainties in the performance of the proposed repository.

Summary

Thermo-mechanical effects for any strategy appear to be repository design concerns rather than site-suitability concerns. There are several ways in which criteria for retrievability and heat flow around waste containers in an above-boiling repository can be met; emplacement drifts or boreholes can be designed that will meet these criteria. From the perspective of thermo-mechanical effects, borehole and drift temperatures should not be viewed as limiting conditions on repository design.

Although it may prove to be efficient for design purposes to minimize thermo-mechanical effects, they do not appear to be a major factor in assessing the performance of the proposed site.

B. Waste Package Issues and Uncertainties

The present reference design calls for radioactive waste going into the repository in two forms: (1) waste packages containing spent fuel assemblies encased in a thin-walled metal container, and (2) high-level waste from reprocessing incorporated in borosilicate glass, encased in a thin-walled metal canister with a thin-walled metal container overpack. The effects of thermal-loading strategies on the waste package can be evaluated best by looking at how the different strategies will affect the performance of the container material, the zircaloy cladding (the outer shell of the individual fuel rods that make up the fuel assemblies), the fuel pellets in the fuel rods (in the case of spent fuel), and the borosilicate glass within the canister (in the case of high-level waste).

Two generic thermal-loading strategies may be considered: above-boiling, which would provide a hotter/dry environment and below-boiling, which would provide a cooler/wet environment.[9] For the purpose of this discussion, container material also refers to canister material.

Below-Boiling Strategies

1. There are several concerns about container material in the below-boiling regime. Generalized corrosion, localized corrosion such as pitting and crevice corrosion, and even microbiological corrosion could take place, leading to an early release of radionuclides. In addition, thin-walled metal containers provide little shielding to contain the radiation emanating from the waste itself. Radiolysis could occur, the products of which may exacerbate corrosion damage. Although some radiolysis could occur at above-boiling temperatures, the adverse effects would be more severe in the below-boiling regime due to the assumed presence of liquid water.

2. The potential concerns for zircaloy cladding in the below-boiling regime, assuming that moisture can reach the fuel assemblies, are similar to those given above for the container material.

3. In both the below- and above-boiling regimes, if oxygen is present, oxidation of fuel pellet fragments from UO_2 to U_3O_8 may take place. The consequent decrease in spent fuel particle size and increase in spent fuel surface area can (only in the presence of water) lead to an increase in colloid formation and dissolution rate. This could be the case in the below-boiling environment if both the containers and cladding are breached. However, oxidation of the fuel pellet fragments may proceed more slowly in this environment than in the above-boiling one.

4. If both the containers and canisters have been breached, the possibility of water in the below-boiling regime creates the potential for the dissolution and hydrolysis of borosilicate glass, which could result in the mobilization of the radionuclides contained in the glass. (However, the rate of hydrolysis may be slower at these low temperatures.)

9 *The material in this section is drawn largely from a presentation made by G. Gdowski on "Waste Form Degradation and Materials Uncertainties" at the Board's October 8-10, 1991, meeting, and from related discussions.*

Above-Boiling Strategies

1. The above-boiling regime raises a number of concerns with respect to the metal container. For example, depending on the metal, there could be microstructural changes caused by long-term ageing, which could possibly weaken the container and increase its susceptibility to corrosion. In addition, if liquid water somehow came in contact with the hot container and evaporated, mineral deposition could exacerbate corrosion.

On the other hand, above-boiling temperatures would encourage the growth of surface oxide layers, which could provide greater protection against container corrosion once temperatures eventually fall below boiling. Above-boiling temperatures could also help to relieve residual stress resulting from welding during container construction. Because of the absence of liquid water in the above-boiling regime, existing and well-known general oxidation models probably could be used, with some confidence, to predict container performance over long time periods, even more than 10,000 years.

2. The potential concerns for zircaloy cladding in the above-boiling regime are the same as those for the container material. Hydride precipitation in the cladding is an additional concern, as it could lead to premature failure. On the other hand, at the higher temperatures associated with the above-boiling regime, cladding stress (usually as a result of radiation hardening) also could be relieved. As with the container material, zircaloy oxide layer growth probably could be modeled with some confidence.

3. If both containers and cladding have been breached and oxygen is present, oxidation of the fuel pellet fragments may occur faster at higher temperatures than in the below-boiling environment. A period of concern could occur after the above-boiling temperatures have been lowered, if liquid water comes in contact with the oxidized fuel. The increased spent fuel surface area resulting from oxidation may enhance radionuclide transport by dissolution and colloid formation. This period could occur after 300 to 1,000 years in the current DOE thermal-loading strategy and after 10,000 years in the proposed extended above-boiling strategy. Using thick-walled, robust containers that would isolate the waste for long periods of time could mitigate these concerns.

Summary

Various modes of waste package degradation, such as dissolution and the chemical reaction of glass with water, may exist during the temperature regimes associated with below- and above-boiling thermal-loading strategies. The Board believes that additional testing, free of large funding fluctuations, will be necessary to fully characterize these modes and evaluate their significance with regard to waste package performance under repository conditions.

One obvious way to reduce concerns about materials degradation and waste package uncertainties would be to design a more robust, long-lived container, which could be proven to resist breaching for 10,000 years or more. Both *thick-walled* containers and *composite* containers should be considered, along with alternative backfills and buffers.

C. Hydrologic Issues and Uncertainties

A key scientific issue associated with thermal loading is to determine the extent to which the different thermal-loading strategies can increase or decrease the likelihood that ground water will come in contact with the radioactive waste containers and subsequently serve as a vehicle to transport radionuclides to the accessible environment. This section discusses the hydrologic issues, that is, the effect of thermal-loading scenarios on the ground-water flow regime.

Below-Boiling Strategies

For any strategy that assumes below-boiling temperatures during the entire, or part of, the 10,000-year regulatory lifetime, the fundamental problem becomes one of understanding and characterizing the essentially ambient (unmodified by high temperatures) hydrologic regime during that period. To do that, four important questions need to be addressed:

1. What is the *conceptual model* that describes ground water flow in the unsaturated zone beneath Yucca Mountain?

Although modeling saturated flow in porous media may be straightforward, modeling unsaturated flow in fractured media is much more difficult (NAS 1990). First of all, the flow of water between the rock matrix (a porous medium) and the fractures that separate that matrix is complex and not easily measured in the field. Second, although in saturated porous media, the flow may attain steady state (time invariant) conditions, the flow in unsaturated fractured media is transient and episodic. Evidence of episodic flow is provided by the discovery of the rapid downward movement of the ^{36}Cl that resulted from nuclear tests at the Nevada Test Site.[10]

2. Assuming that a satisfactory conceptual model of ground-water flow in the unsaturated zone can be developed, the next question is whether this model can be expressed in a computational model that will allow the meaningful prediction of ground-water flow over the next 10,000 years.

To date, most modeling of flow in fractured media has made use of the *equivalent continuum model*. That is, it is assumed that the flow properties of both the fractures and matrix can be approximated by using a porous medium with gross properties chosen to reflect the presence of fractures. A somewhat more sophisticated model is the *dual porosity model*, which assumes two average porosities, one reflecting the rock matrix and the other representing the fractures. The most direct approach is through the use of the *discrete fracture model*, which assumes and makes use of knowledge of individual fracture locations and characteristics. Although this latter model is the most accurate, it represents a major computational effort, even in two dimensions. To date these models have been used primarily for theoretical studies (NAS 1990). Hydrologists used a discrete fracture model on the Yucca Mountain Project to explain, among other things, how ^{36}Cl (discussed above) could penetrate to the depths at which it was observed.[11] However, a sufficiently detailed discrete fracture model that would be capable of describing the three-dimensional flow regime in the unsaturated zone around Yucca Mountain appears to be beyond the reach of existing computational abilities.

3. Assuming that a computational model is feasible, a detailed description of the fractures (and their properties) that exist within the repository block is a formidable task. Although exploration at depth by means of an exploratory studies facility (ESF) will greatly increase our knowledge of the existing fracture network, the question remains whether it will be sufficient to provide a robust and unchallengeable view of the flow regime. Extrapolation of the ESF data away from the exploratory drifts and boreholes will always be necessary.

4. A related problem is with determining the future climate in the Yucca Mountain region. This will be necessary to establish the precipitation and the resultant infiltration of water into the repository block. In the geologic past, pluvial climates (those associated with higher precipitation and lower potential evapotranspiration) have existed in the region during glacial epochs. The posed question becomes, how well can precipitation and evapotranspiration be predicted 10,000 years into the future. Lacking a definitive prediction, the issue becomes more one of estimating reasonable upper and lower bounds on which the scientific community can agree.

Above-Boiling Strategies

According to proponents[12] of the above-boiling strategy, the main hydrologic advantage is the creation of a dryout zone within the repository such that no water can reach the waste containers. This, they argue, will avoid most of the problems and uncer-

10 *Norris, A.E., "The use of chlorine isotope measurements to trace water movements at Yucca Mountain." Proceedings of the American Nuclear Society Topical Meeting on Nuclear Waste Isolation in the Unsaturated Zone (Focus 89), Las Vegas, NV, Sept. 17-21, 1989.*

11 *Buscheck, T.A. "Role of Non-Equilibrium Fracture-Matrix Flow in Site Characterization." Presentation to the Board, June 25-27, 1991.*

12 *See for example, Buscheck, T. A. "Hydrogeologic Uncertainties." Presentation to the Board, October 8-10, 1991; or Buscheck, T. A. and J. J. Nitao, "The Impact of Thermal Loading on Repository Performance at Yucca Mountain." Proceedings of the Third Annual International Conference on High Level Waste Management, April 12-16, 1992.*

tainties associated with characterizing the ambient hydrologic regime described above. Fractures would be dry; there would be no fracture flow; and effects of the pluvial climate would be mitigated. An additional level of assurance would be provided by the creation of a hydrothermal “umbrella,” or umbrellas, above the repository. This umbrella effect assumes that when the water vapor driven away from the repository eventually reaches cool enough rock and condenses, it will flow down the edges of the repository as if there were a gigantic umbrella protecting the repository. A modification of this umbrella effect would occur if the thermal effects were more localized. In this case, the condensed water vapor would flow through the repository between, and therefore avoiding, the heated regions around the individual waste packages. Four questions associated with the above-boiling strategy need to be addressed:

1. How valid are predictions of an extensive, long-lasting dryout region when they are, as is currently the case, based on an equivalent continuum model?

Proponents of the above-boiling strategy argue that, using more sophisticated models, the explicit incorporation of fractures into the calculations would enhance the dryout predicted by the equivalent continuum model through the formation of the hydrothermal umbrella. This has yet to be proven and may well be beyond the capability of current modeling methodology.

2. How well can in-situ testing validate predictions of extensive, long-lasting dryout?

The proponents argue that the heater tests in G tunnel, not far from Yucca Mountain[13], demonstrated that the ECM accurately calculated both temperature and dryout behavior, and that the existence of a hydrothermal umbrella can be inferred. The most important tests that have been proposed, however, will involve heaters placed at different hydro-stratigraphic intervals to simulate thermal/ hydrologic behavior of larger rock volumes. Significant scaling problems still exist with this approach. Two particular concerns are (a) the temporal scaling from tests conducted over several years to simulate behavior over hundreds and perhaps thousands of years and (b) the spatial scaling of tests conducted in a relatively small volume of rock to the large, heterogeneous rock mass that makes up the repository block.

3. If the current thermal-loading strategy (which assumes an above-boiling environment for only part of the regulatory lifetime) is adopted, both above-boiling and below-boiling environments will have to be accounted for. This raises at least two questions: Will the need to characterize two different hydrologic regimes (both changing in time and space) result in a large increase in uncertainty? Will the below-boiling hydrologic regime occurring after extensive heating of the rock be significantly different from the current ambient regime?

4. The existing site suitability (10 CFR 960) and licensing (10 CFR 60) regulations include groundwater travel time criteria that call for a preemplacement travel time of greater than 1,000 years from the *disturbed zone* to the accessible environment. The disturbed zone is defined as that portion of the surrounding rock whose physical or chemical properties have changed as a result of construction or “as a result of heat generated by the emplaced radioactive waste such that the resultant change of properties may have a significant effect on the performance of the geologic repository” (10 CFR 60). Scientists need to evaluate how a thermally induced extension of the disturbed zone will affect the ability of the Yucca Mountain site to satisfy this criterion.

Summary

It is obvious that there are many uncertainties associated with both the below- and above-boiling strategies. Based on the hydrologic evidence, there is no basis for choosing a strategy at this time. It is also

13 *Buscheck, T. A. and J. J. Nitao. “Modeling Hydrothermal Flow in Variably Saturated, Fractured, Welded Tuff During the Prototype Engineered Barrier System Field Test of the Yucca Mountain Project.” Proceedings of the Fifth NRC Workshop on Flow and Transport through Unsaturated Fractured Rock, University of Arizona, Tucson, AZ, January 7-10, 1991.*

apparent that no single approach alone, that is, modeling, field mapping, or thermal testing, can provide a defensible rationale for this choice. The Board believes that the DOE needs to review existing plans (the SCP) to ensure that the relevant information will be developed through critical field and laboratory tests in such a way that a prudent choice of thermal-loading strategy eventually can be made. As part of this review, the DOE should determine whether natural analogues, such as those near existing natural thermal sources (for example, hot springs), can play a useful role. (Natural analogues were discussed in the Board's second and fourth reports.)

D. Geochemical Issues and Uncertainties

The impact of thermal loading on the geochemical environment can significantly affect the release of radionuclides via ground water to the accessible environment. A prime factor affecting the transport of radionuclides is sorption, that is, retardation (of transport) through the binding of radionuclides by the surfaces of geologic materials along the flow path. The principal minerals that can sorb radionuclides at Yucca Mountain are zeolites (for example, clinoptilite and mordenite) and clays such as smectites. These minerals occur in close proximity to the proposed repository horizon. Modification of their sorptive abilities, as a result of temperature increases, has always been a topic of interest to those concerned with the efficacy of the geologic barrier to isolate waste. Also important is the effect of thermally induced geochemical and mineralogic changes on the flow regime itself.

Issues

Because the effect of thermal loading on geochemical processes is primarily gradational, and not simply a function of the temperature being above or below boiling, the issues and uncertainties discussed below are not grouped by thermal-loading strategy.[14]

1. In general, geochemical alterations can occur at all temperatures. Increasing the thermal load serves to increase both the intensity of these alterations and the volume of rock affected. In this context, above-boiling strategies serve to increase uncertainty.

2. In general, at lower temperatures, kinetics (rates of chemical reactions) govern the rock / water chemistry and, therefore, the retardation of radionuclide transport. At low temperatures, the predictability of these reactions is impaired by their complexity and slowness. At higher temperatures, thermodynamic equilibrium may be achieved, and it will govern the water / rock chemistry. The calculation of stable mineral assemblages and coexisting water chemistry at these high temperatures, however, is impaired by the paucity of relevant thermodynamic and experimental data.

3. The effects of increasing temperature on the sorptive properties of minerals are complex. Experiments and model calculations indicate that these effects differ with the radionuclide (for example, cesium or strontium) being considered and the nature of the sorbing solid phase. Another factor that affects sorption is the concentration of silica, which is controlled by the solubility of the least stable silica polymorph (crystal form) present. Thus, if the least stable silica polymorph is the more soluble glass or cristobalite, silica concentration is high and the formation of sorptive minerals such as clinoptilite, mordenite, and smectite is favored. These minerals may be formed by the alteration of volcanic glass at low temperatures (e.g., 40°C).

On the other hand, if the least stable silica polymorph present is the less soluble quartz, silica concentrations will be low, and the less sorptive minerals such as analcime and the feldspars are favored. Increasing the temperature increases the rate at which quartz is formed, thereby favoring the formation of the less sorptive minerals. The rate of this transformation depends on silica concentration and temperature. Thus, for example, it has been estimated that transformations to less sorptive miner-

14 *Material in this section is drawn largely from presentations made by B. Viani on "Geochemical Uncertainties," and D. Bish on "Mineralogical Uncertainties" at the Board's October 8-10, 1991, meeting, as well as from related discussions.*

als, which may take tens or even hundreds of thousand of years at 100°C, could take only hundreds of years at 200°C.

4. An additional factor that affects thermally induced mineralogic change is the partial pressure of water (ratio of water vapor pressure to total vapor pressure) in rock pores and fractures. The retention or loss of water molecules to zeolites and clays is dependent on temperature and the partial pressure of water. The loss or addition of water molecules will produce volume changes in some minerals. It appears that these volume changes do not materially affect sorption but can impose stresses on the rock and thereby possibly alter its permeability and the flow regime.

5. Another geochemical effect that can alter the flow regime is the precipitation of minerals. The above-boiling thermal-loading strategy involves the evaporation of water near the hot repository and its condensation some distance away. As the water condenses, cools, and flows downward toward the saturated zone, mineral precipitation will occur along fracture pathways. If some of the condensed water flows back toward the repository and re-evaporates, secondary minerals may again precipitate. The net effect of this precipitation may be a reduction in rock permeability and porosity.

Summary

The effects of thermal loading on geochemistry are complex and dependent upon a multitude of factors. If one wants to minimize the complexity, lower thermal loads, which affect smaller rock volumes, are preferred. On the other hand, increased thermal loads would appear to have less of a direct effect on sorption and the retardation of radionuclides than they would on the flow regime itself. Predicting the effects of precipitation and volumetric mineral phase changes on permeability and porosity in a fractured medium will be a difficult problem. The benefits of an increased dryout zone will have to be weighed against these increases in uncertainty. Field testing, natural analogues, and laboratory and modeling studies may all be needed to resolve this issue. The Board believes that the DOE needs to review existing plans in this area to ensure that critical tests are performed and that the relevant information will be developed for making a prudent choice of thermal strategy.

E. Performance Assessment Issues and Uncertainties

Performance assessment is the primary tool for predicting the ability of the proposed high-level waste management system to contain and isolate radioactive waste. Researchers use various models and parameters as input to the performance assessment process. By varying the models and the parameters used, the impact of different assumptions upon the release of potentially harmful radionuclides can be estimated. As a result, it would appear very useful to use this type of performance assessment to evaluate the ability of the different proposed thermal-loading strategies to enhance waste containment and isolation.

Although the DOE has not presented the results of a performance assessment-based evaluation of thermal loading, the Electric Power Research Institute has carried out such a study and presented some preliminary conclusions of its study at the Board's October thermal-loading meeting.[15] Some of the EPRI conclusions are:

1. Nongaseous releases are not very sensitive to the assumed (see discussion below) thermal-loading strategies.

2. Waste package behavior, which is the key ingredient in determining the *source term* (the rate at which radionuclides are released to the host rock), is a controlling factor.

3. The dominant releases are associated with soluble radionuclides.

15 Presentations by R. A. Shaw and others on "Performance Assessment: Effects of Thermal Loading," at the Board's October 1991 meeting. The conclusions discussed in the above text are those of the presenters unless otherwise indicated.

4. Although the release of gaseous ^{14}C was not included in the total system performance assessment presented, initial EPRI studies indicate that this mode of release may be exacerbated by higher thermal loads, and that travel times to the accessible environment may be shortened considerably. On the other hand, it has also been suggested that an increase in temperature could promote the precipitation of calcite near the repository horizon, which may trap a portion of the ^{14}C, delaying its release to the accessible environment.[16]

Any performance assessment is very dependent on its assumptions. In the EPRI study, for example, thermal-loading strategies were simulated by assuming waste container surface temperatures that are themselves controlled by different heat transfer regimes in the surrounding rock. The thermal-loading strategy that maintains temperatures above boiling over 10,000 years was not included in the simulations. Similarly, differences in the hydrology (flow regime) were not modeled explicitly, but the effects were assumed to be reflected in the different assumptions about heat transfer.

It remains to be seen whether the results, particularly the insensitivity of nongaseous radionuclide releases to thermal-loading strategies, can be substantiated by further studies and tests. The Board cannot endorse or reject these conclusions at this time. However, the Board does believe that the insights gained through iterative and validated performance assessment could play an important role in making the prudent choice of a repository thermal-loading strategy. The Board urges the DOE to incorporate alternative thermal-loading strategies into its ongoing performance assessment efforts.

16 *Comments by R. B. Codell at the Board's October 1991 meeting; and R. B. Codell and W. R. Murphy, "Geochemical Model for ^{14}C Transport in Unsaturated Rock." Proceedings of the Third Annual International Conference on High Level Radioactive Waste Management, April 12-16, 1992.*

Chapter 4
Implications of Thermal Loading for the U.S. Radioactive Waste Management System

In its *First Report to the U.S. Congress and the U.S. Secretary of Energy*, the Board identified "thermal loading of a repository" as one issue that would have a large influence on the level of uncertainty on a repository's long-term performance. The Board described thermal loading (thermal output of emplaced spent fuel per unit area of repository, usually expressed as kilowatts per acre) as a "cross-cutting issue." A thermal-loading strategy describes a way to achieve a given range of temperatures within a repository over a chosen period of time. The thermal-loading strategy chosen for a geologic repository will affect most other system components, including how spent fuel is packaged, stored, and transported, as well as the design, capacity, performance, and cost of the repository.

At the October 1991 Board meeting, U.S. as well as Canadian, German, and Swedish experts provided their perspectives on the issue of thermal loading in general, and on the U.S. strategy in particular. As a result of this meeting, the Board has reached a number of conclusions and makes several recommendations.

Although the candidate repository site has not yet been characterized, nor found to be suitable, the DOE has adopted a baseline thermal-loading strategy that calls for waste package temperatures to remain above the boiling point of water for 300 to 1,000 years, then fall below boiling for the remaining period of isolation. Because an adequate evaluation of the *technical merits and uncertainties* of various thermal-loading strategies has not yet been performed, the Board believes that making a commitment to a specific strategy and corresponding repository and waste management system design is premature.

The Board would like to emphasize that it has no reason at this time to agree or disagree with the DOE's baseline thermal-loading strategy. One major conclusion reached as a result of the October meeting is that many questions remain unanswered — questions about the advantages and disadvantages of different thermal-loading strategies, as well as questions about the effects of elevated temperatures on the hydrogeologic environment. For this reason, the Board was pleased to learn in early February 1992 that, under the auspices of the management and operations contractor, an analysis is underway that proposes to evaluate several alternative thermal-loading strategies and their implications for the waste management system. The Board hopes that during the upcoming analysis, the DOE will study carefully the technical merits of its current thermal-loading strategy *in comparison* to alternative strategies, thereby taking into account the implications of alternative strategies on the various components of the whole waste management system. The primary goal of this kind of study should be to ensure system safety throughout the life of the repository with a minimum of uncertainty. Sound technical analysis should not be sacrificed to meet what may be unrealistic and unnecessary program schedules. The Board looks forward to hearing more about this analysis as it evolves.

The Board has repeatedly stated its view that waste disposal must be looked at as an *integrated* system. For example, thermal-loading decisions control the repository design, which in turn affects how and what decisions are made about other system components — such as the emplacement concept or the waste package design. Yet, currently less than 2 percent of the DOE's requested appropriations for fiscal year 1993 is allocated for research into the development of the "waste package," which includes the evaluation and development of long-lived waste packages, emplacement alternatives, and other engineered barrier system concepts. The continuing deemphasis of waste emplacement research appears inconsistent with an intention to evaluate alternative thermal-loading strategies, and to subsequently develop an engineered barrier system in light of those evaluations.

The Board is concerned about the process through which the repository conceptual design has evolved. It appears that above-boiling temperatures for relatively short time periods have been assumed from the beginning, and many of the uncertainties identified in the early years remain. In most large, complex projects such as this, an iterative process is used to analyze and test multiple hypothetical strategies. The important components of the various subsystems are identified, and alternatives are examined and assessed within the parameters of the overall system. As this process continues, the system and its components are adjusted until a final "preferred" choice can be made. Experience gained by Board members over the years corroborates insights offered by Canadian, German, and Swedish colleagues during the three-day meeting: It is wise to keep options open until competing strategies are thoroughly evaluated when designing such a complex system. Only in this way can new information that will be gained during technical analyses, assessments, testing, and underground excavation of the site be incorporated into the evolving repository and waste management system designs.

The following sections discuss the systemwide implications of thermal loading raised at the October meeting. The Board believes it is crucial to address thermal loading as the "cross-cutting" issue that it is by looking at the short- *and* long-term implications that various strategies have for the entire waste management system.

Systemwide Implications of Thermal Loading

As mentioned above, thermal-loading decisions will significantly affect the design of many functions and components of the waste management system. Such functions may include the waste emplacement schedules and plans, interim spent fuel storage, mix of spent fuel loaded into the waste packages, and transportation. Affected components may include the engineered barriers (e.g., the waste package), spent fuel storage and handling devices, and shipping containers.

Thermal-loading decisions may have an immediate impact on waste emplacement and associated costs. For example, one thermal-loading strategy (the long-term above-boiling strategy discussed in Chapter 3) calls for waste emplacement at high areal power density. This could be accomplished by spacing waste packages closer together than called for in the SCP, or by adopting higher capacity waste packages. The use of higher capacity waste packages could favor emplacement of more robust waste packages in drifts as opposed to the current baseline strategy that calls for emplacing smaller diameter, thin-walled containers in boreholes in the floors of drifts. Although they could cost more than the thin-walled containers per unit of spent fuel, more robust containers would provide shielding protection absent in the current SCP waste package design, thus making feasible many emplacement configurations very different from the SCP baseline. This might allow significant savings to be achieved *for the overall waste management system* through reductions in emplacement costs (e.g., reductions in repository construction costs and reduction—perhaps elimination—of the need for elaborate shielding devices required to handle the thin-walled containers). It also is conceivable that a large, more robust, long-lived waste package could provide both long-term safety and redundancy that could enhance public acceptance and repository licensing with savings for each year gained. Although such economic trade-offs have not been studied, this example illustrates some important questions that could be raised during system studies of alternatives to the baseline strategy.

Other emplacement-related issues that need to be considered within the parameters of differing thermal-loading strategies include repository layout, waste package emplacement methods, retrievability, alternative backfill materials and methods, safeguards, effects from enhanced cooling systems, overall system performance, and cost.

Another example of how thermal-loading decisions significantly affect other components of the waste management system is easily illustrated through a discussion of interim storage requirements for spent fuel. The long-term above-boiling strategy could keep the near-field host rock temperatures above boiling over a 10,000-year span by emplacing fuel aged at least 60 years at a high areal power density (approximately 115 kilowatts / acre). The ageing requirement of this strategy is considerably longer than the 10 years envisioned in the SCP. "Ageing" can be accomplished in a variety of ways. The fuel could continue to age at reactor sites. Or, it could be aged in-situ at a repository using drift ventilation to avoid overheating. The spent fuel also could be stored temporarily at reactor sites and then transferred to a central monitored retrievable storage facility, for example, from which it later would be transferred to a repository for final disposal.[1]

Additional ageing would entail additional storage costs, of course. For example, costs for expanded on-site storage facilities would increase at many reactors. However, there may be significant cost savings *for the overall waste management system* if this strategy actually allows the accommodation of much larger amounts of spent fuel in a given repository area than envisioned in the SCP, which currently implies the need for a second repository. Also, drift emplacement of larger waste packages in smaller diameter drifts, rather than in boreholes in larger diameter drifts, could provide cost reductions.

If the DOE were to assess thoroughly the implications of thermal-loading strategies for interim storage, at-reactor storage needs would have to be included as part of the examination. More important, long-term storage may become a defacto part of the system plan as a natural result of further delays in repository development.

Other questions arise as well: What are the implications of a particular thermal strategy for storage technology (e.g., for the dry storage devices that already are being designed and licensed by those utilities that have run out of pool space)? Under any realistic scenario, spent fuel will be transported from the reactor cooling pools to on-site dry storage and from there either directly to the repository, or to a monitored retrievable storage facility and on to the repository. Current plans call for the fuel to be shipped in massive, heavily shielded casks. This raises several questions with significant system implications. Could one container be designed for storage and transport? Could such a dual-purpose container reduce handling and thereby offer improved protection of human health and the environment, or reduced overall waste management system costs, or both? What other benefits could be derived from a dual-purpose or, an all-purpose cask (for storage, transportation, and disposal)? What regulatory obstacles are there, if any, to deploying these types of technological concepts, given the current repository concept? Does the nature of the obstacles change for robust waste package / drift emplacement concept?

The Board's three-day meeting on thermal-loading strategies underscored just how interrelated the storage, transportation, and disposal functions of the system are. These discussions highlighted the importance of one fundamental question: *How do changes in major system components affect one another, and what are the trade-offs for the system as a whole?* Other important and complex questions surface when alternatives to performing just one of the functions — in this case, disposal — are examined. The Board is convinced that these system questions should be addressed thoroughly before major tech-

1 *At this time, the DOE's plans call for a limited capacity monitored retrievable storage facility to begin accepting spent fuel for storage in 1998. However, with its legal capacity limit currently at 10,000 metric tons, such a facility will not obviate the need for on-site storage.*

nical decisions, such as thermal-loading strategy, are made.

Systems analysis is one way to develop insights into complex system and subsystem issues. This analysis can greatly facilitate the design of the program by (1) identifying technical goals and priorities; (2) justifying R&D and testing decisions; and (3) tracing the multitude of data that will be gathered and analyzed as site exploration and repository development progress.

Conclusions

1. Thermal loading is one of the most fundamental parameters affecting the design and long-term performance of a repository. The DOE's reference repository design for the proposed Yucca Mountain site — as described in the SCP and the draft Mission Plan Amendment, and as presented to the Board by the DOE — prescribes a thermal-loading strategy that will produce waste package and near-field host rock temperatures well above the boiling point of water for a period of 300 to 1,000 years, after which temperatures will drop below boiling.

2. The DOE's current baseline thermal-loading strategy for Yucca Mountain is based on the hypothesis that a region surrounding the waste packages will dry out for the 300-to-1,000-year period and that liquid water will not be present to cause container erosion and to transport of radionuclides to the accessible environment. This hypothesis is as yet unproven. Therefore, a firm scientific and technical basis for justifying the DOE's baseline thermal-loading strategy for the Yucca Mountain site does not exist.

3. The vast majority of the DOE's recent work on thermal loading has involved *modeling* its above-boiling, baseline thermal-loading strategy, assuming the conditions that would exist inside the proposed repository at Yucca Mountain. This strategy and its associated critical hypotheses need to be validated through large-scale, long-term underground tests.

4. The specific details of the DOE's proposed thermal-loading strategy appear to have evolved incrementally, and in a somewhat unstructured manner, during the last two decades. Important documents related to geologic disposal clearly suggest that high thermal loads have always been assumed by the DOE for repositories in this country, regardless of the disposal environment.

5. The DOE's current baseline thermal-loading strategy for the Yucca Mountain site clearly is consistent with accomplishing two objectives: It would allow the DOE to quickly demonstrate a capability to dispose of spent fuel (by 2010), and it would minimize the need for long-term spent fuel storage either at the reactors or at a monitored retrievable storage facility. In addition, the conceptual design for the DOE's reference waste package is intended to meet only the minimum NRC performance requirements. The Board believes it is important that the waste management schedule reflect the goal of safe waste isolation for several thousand years through a combination of redundant geologic and engineered barriers (including robust, long-lived waste packages).

6. A comprehensive and systematic analysis of alternative, and potentially better, thermal-loading strategies (e.g., below boiling, or above boiling for 10,000 years or more) for the proposed Yucca Mountain site has not yet been completed. As a result, a *technical basis* for the DOE's current thermal-loading strategy for the Yucca Mountain site does not exist.

7. The capacity of any repository for spent fuel and high-level waste is directly related to thermal loading. Therefore, realistic estimates of the waste disposal capacity of the proposed Yucca Mountain site can be made only after underground exploration has been conducted and a thermal-loading strategy confirmed through a balanced combination of modeling, field mapping, laboratory testing, and underground tests. If thermal loads lower than those proposed by the DOE's reference repository design are found to be more appropriate, "expansion" areas abutting the proposed 1,520-acre repository site might be necessary. Also, expansion areas may be required if structural features (e.g., faults) identified during underground exploration must be avoided during later repository construction.

8. The choice of thermal-loading strategy is an engineering decision that affects both the ability of the engineered barrier system to contain harmful ra-

dionuclides and the ability of the natural barrier (primarily the host rock and hydrologic regime) to retard radionuclide migration to the accessible environment should waste packages be breached. When addressing issues related to thermal loading, it becomes evident that the engineered and natural barriers are not independent entities, but do interact. When evaluating the effects of options, such as the choice of a thermal-loading strategy, on individual barriers, what is always "good" for one may not always be "good" for another. An informed choice in such situations requires an evaluation of the advantages and disadvantages of the different options for the overall repository system.

9. A *system* for managing the nation's high-level radioactive waste is composed of various interrelated components involved in storage, transportation, loading wastes into disposal packages, and disposal in an engineered, geologic repository. Examples of specific system considerations include waste package definition, waste mix per package, modes of transportation, thermal-loading strategy and repository design, waste emplacement modes, testing plans and facilities, and overall system costs. Decisions about, or changes to, any system components could significantly affect other components of the system. For example, the choice of a thermal-loading strategy could significantly affect waste package performance and ground-water transport.

10. The need for comprehensive, systemwide tradeoff studies is reaching a crucial stage. For example, the exploratory studies facility will enter the final design phase within the next six to eight months. However, without these systemwide trade-off studies, decisions about the facility's design could negate repository configurations later shown to be preferable. Such a situation could conceivably jeopardize or seriously delay repository licensing and greatly increase costs.

Board Recommendations

1. The Board recommends that the DOE thoroughly investigate alternative thermal-loading strategies that are not overly constrained by a desire to rapidly dispose of spent fuel. This investigation should involve a systematic analysis of the *technical advantages and disadvantages* associated with the different thermal-loading strategies. An assessment of each strategy's implications for other elements of the waste management system also should be undertaken.

2. In assessing the different thermal-loading strategies, it is critical that special attention be paid to evaluating the uncertainties and, in particular, the critical hypotheses associated with each strategy. The Board strongly encourages the DOE to review its research plans to ensure that this evaluation be carried out through a balanced combination of modeling, field mapping, laboratory testing, long-term, large-scale underground testing, and, if appropriate, the study of natural analogues. This information could then allow the timely selection of a prudent thermal-loading strategy.

3. Since thermal loads lower than those proposed by the DOE's reference repository design could require the use of expansion areas adjacent to the proposed 1,520-acre repository site, any exploratory work in these expansion areas should be conducted with deliberation to avoid disqualifying the areas for potential use later on.

4. Care should be taken in making critical decisions, especially irreversible decisions, that could have negative implications for other components of the waste management system. This is particularly important in light of the fact that important systemwide trade-off studies have not been completed.